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Posterior-anterior Cephalograms: Validity of Landmarks and Reference Lines

by

Biljana Trpkova



A Thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfillment of the requirements for the degree of Master of Science

In

Orthodontics

Department of Dentistry

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Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Posterior-anterior Cephalograms: Validity of Landmarks and Reference Lines** by Biljana Trpkova in partial fulfillment of the requirements for the degree of Master of Science in Orthodontics.

ABSTRACT

Posterior-anterior (PA) radiographic landmarks are used in cephalometric analyses to represent various anatomic structures of interest. For assessment of vertical and transverse dento-facial asymmetries relative measurements from the landmarks to different reference lines are taken.

The first objective of this study was to determine the validity of commonly used PA landmarks for depicting various transverse and vertical changes in the dento-facial complex. The relationship between measurements of change in the transverse direction and changes in the anterior-posterior dimension of landmarks was also investigated.

Regression analyses revealed that all PA landmarks represented 90% or more of the transverse changes in truth. Vertical changes were adequately represented by ten peripheral landmarks, including Condyle Superior Right and Left, Condyle Center Right and Left, Jugal Point Right and Left, Maxillary and Mandibular First Molar Right and Left. The other ten peripheral landmarks showed less than 90% of the changes created in truth. Menton, Incisor Inferior, Incisor Superior and Anterior Nasal Spine showed the least ability to represent vertical changes. However, the increments of vertical changes of these four midline landmarks were smaller than the error of measurement and it was not possible to establish their validity. Only one landmark showed significant association between the changes in the anterior-posterior direction and its ability to show transverse changes during vertical rotations of the dento-facial complex.

· The second objective was to determine the validity of ten horizontal and fifteen vertical reference lines that have been previously used in PA analyses for assessment of dento-facial asymmetries. Linear regression analyses were used to compare the created asymmetries measured in truth, and cephalometrically, relative to the individual reference lines. The adjusted R-squared values for all 10 horizontal lines indicated excellent agreement between the true asymmetries and cephalometric asymmetries. Ten vertical lines accurately represented transverse asymmetry. In general, vertical lines constructed between two midline points were not valid, while the Best Fit Line as well as all lines constructed as perpendiculars through midpoints between pairs of orbital landmarks showed excellent validity. Crista Galli-Anterior Nasal Spine and Nasion-Anterior Nasal Spine had the least validity for transverse measurements and should not be used in cephalometric analysis of asymmetries.

DEDICATION

I dedicate this work to my motherland, Macedonia.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Posterior-anterior (PA) cephalograms are standard radiographic views that depict the width and angulation of the dental arches in relation to the cranium, the relative position of the upper and lower dental midlines to each other and to the dento-facial structures, the vertical and transverse dimensions of the maxilla and the mandible, and the inter-relation between the maxilla and mandible and the rest of the craniofacial complex. They are the most commonly used radiographic views for diagnosing skeletal dento-facial asymmetries in orthodontic and orthognathic patients. Another use of PA cephalograms is longitudinal evaluation of changes in the transverse and vertical dimensions due to growth as well as a result of orthodontic or orthognathic treatment.

Some of the challenges associated with PA cephalometry have been well documented in the literature. In general, two categories of errors have been identified, errors of projection and errors of landmark identification.

- I. *Projection errors*- errors due to the technical arrangement of the roentgen apparatus and patient positioning. As a result of divergence of the x-ray beam, the imaged object is magnified and distorted, since points closer to the film are less magnified than points farther from the film. Only points that coincide with the axis (central beam) of the x-rays will not be magnified.¹ Patient positioning is important to control head orientation. A cephalostat can minimize head rotation but has to be secured against soft tissues, which can distort easily. Asymmetries of the patients' external auditory meati can also affect head position. The PA view is particularly sensitive to head rotation around the vertical and transverse axis.

Rotation about the vertical axis will affect transverse relationships. When the head rotates around the transverse axis, the vertical relationships will change, while the transverse relationships remain essentially unchanged. It has been shown that five-degree rotation of the skull around these axes produces insignificant amount of error. Rotation greater than five degrees is likely to be recognized at the time of imaging.²

II. *Landmark identification errors*- accurate identification of PA landmarks depends on multiple factors including density and sharpness of the radiographic image, the anatomic complexity and superimposition of hard and soft tissues, observers' experience when locating a particular landmark, and the precise definition of the landmarks' location. Two features are important to consider when choosing landmarks for analysis:

- ◆ Landmark validity-the extent to which, in the absence of measurement error, the value obtained represents the anatomic structure of interest.

- ◆ Landmark reproducibility- the accuracy with which a landmark can be identified on repeated occasions.³

Landmarks reproducibility has been well documented in the literature. Each PA landmark demonstrates its own envelope of error, characterized by magnitude and distribution along the horizontal and vertical axis.^{1,4} The choice of landmarks used in a cephalometric analysis should be guided by the objective of the analysis. Landmarks with large horizontal identification error should be avoided for transverse measurements, while landmarks with large vertical error should not be used for measuring vertical dimensions.¹ El Mangoury et al.⁴ studied the reproducibility of thirteen landmarks on the PA image.

Dental landmarks were found less reliable as compared to skeletal landmarks. Major et al.¹ determined the reproducibility of 52 landmarks and concluded that many landmarks used in PA cephalometrics have unacceptable magnitude of error. Landmark identification error is generally larger when more than one observer is involved in the analysis, despite a prior consensus on landmark definition and location.¹

Another difficulty in PA cephalometry is the choice of adequate reference lines for a cephalometric analysis. Various horizontal and vertical reference lines have been used in the literature, although none has been proven more valid than others.⁵ Structures to be used as reference system should be stable, have a high degree of reproducibility and a high degree of symmetry. Two methods can be used to construct vertical reference lines:

1. Perpendicular Line Method- a horizontal line connecting a pair of bilateral landmarks is drawn and a vertical line perpendicular to the horizontal reference and passing through a mid-anatomical point or the midpoint between the pair is constructed to represent the craniofacial axis. Landmarks that are in the proximity of the cranial base, such as Zygomatico-frontal sutures and Crista Galli have been used.⁶ Orbital landmarks have been used frequently in the construction of a horizontal reference line. Lund⁷, Stabrun⁸, Alavi et al.⁹ have used the superiormost point of the orbital outlines to construct a horizontal reference line. The superior and lateral orbital contours are stable reference areas after eight years of age⁹ and also have an acceptable margin of identification error.

¹ Johnston⁵ suggested that the vertical reference line does not have to be perpendicular to the horizontal reference. He proposed the intersection of the superior border of the greater wing of the sphenoid bone with the lateral orbital margin for construction of a

horizontal reference line. In his study the landmarks most appropriate for a vertical reference line were the bisector of the line through the intersection of the inferior border of the sphenoid bone and the lateral orbital margin, and the midpoint of the nasal septum. Grummons et al.¹⁰ developed a comprehensive PA analysis to provide information about specific locations and amounts of facial asymmetry. They used several horizontal reference lines located in different regions of the face to measure vertical relationships. Transverse relationships were measured to a vertical reference line constructed between Crista Galli and Anterior Nasal Spine.

Best-fit Line Method- In the best-fit line method multiple pairs of bilateral landmarks are located, joined with horizontal lines and then bisected. A vertical reference line is constructed by the least squares method. The advantage of this method is that if a midpoint is obviously off in relation to the other midpoints of the cranium and face, it can be excluded when drawing the axis. Best-fit lines have been promoted as the most valid reference lines in PA cephalometric analyses.⁵

1.2 STATEMENT OF THE PROBLEM

Posterior-anterior cephalograms are the most commonly used radiographic tools for assessment of transverse and vertical dento-facial relations and for evaluation of asymmetry. In the hierarchy of errors that can be produced while interpreting PA cephalograms, landmark validity is the first important factor to be considered. Validity is the extent to which, in the absence of measurement error, the value obtained represents the anatomic structure of interest. Lack of validity of PA landmarks can undermine the accuracy of the entire PA cephalometric analysis. To date, the validity of commonly used PA cephalometric landmarks remains unknown.

Another important issue when dento-facial asymmetry is in question is the choice of adequate reference system. The structures to be used as reference should be stable, symmetric and separated from the areas of interest. Separation of the reference system from the lower facial skeleton is required to ensure its stability from the effects of dento-skeletal changes due to orthodontic and orthognathic treatment. It would be preferable to avoid the use of maxillary or mandibular midline landmarks in the construction of vertical reference lines. Unfortunately, many PA cephalometric analysis rely on reference lines that do not fulfil these criteria. In addition, there are no studies that have verified the accuracy of various reference lines in representing dento-facial asymmetries.

- 1.3 PURPOSE

The first goal of this study is to determine the validity of commonly used posterior-anterior (PA) cephalometric landmarks. Validity will be defined as the accuracy of landmarks to represent vertical and transverse locations of dento-facial structures in the absence of other sources of measurement error. The validity results from this study can be combined with data on landmarks identification error obtained from previously published research studies. Compound information on landmarks validity and landmarks identification error can provide useful guidelines for selection of appropriate landmarks for PA cephalometric analyses.

The second purpose of this study is to determine the validity of various horizontal and vertical reference lines that have been used in previously published PA analyses for assessment of dento-facial asymmetries.

1.4 RESEARCH QUESTIONS

1. What is the validity of commonly used posterior-anterior landmarks for representing various dento-facial structures on PA cephalograms?
2. Do all commonly used PA landmarks have adequate validity when measuring dento-facial asymmetry?
3. Is there a difference between the validity of PA landmarks for representing transverse and vertical dimensions?
4. Is the validity of PA landmarks affected by the lack of a third dimension (anterior-posterior axis)?
5. What horizontal reference lines are adequate for use in PA cephalometric analyses for measuring vertical dimensions?
6. What vertical reference lines are adequate for use in PA cephalometric analyses for measuring transverse dimensions?

-1.5 NULL HYPOTHESES

1. There is no difference between increments of change in the position of anatomic landmarks measured in truth and from posterior-anterior cephalograms.
2. There is no difference in the validity between commonly used cephalometric landmarks.
3. There is no difference between the ability of individual landmarks to represent transverse or vertical changes.
4. The changes in the anterior-posterior direction are not significantly related to the ability of the PA landmarks to show changes in the transverse and vertical direction.
5. There is no difference in the validity of various horizontal reference lines for measuring vertical asymmetries
6. There is no difference in the validity of various vertical reference lines for measuring transverse asymmetries.

1.6 LITERATURE REVIEW

1.6.1 The History of Posterior-anterior (PA) Cephalometry

From 3-D Enterprise to a Tool for Measuring Asymmetries

Over the past seven decades cephalometry, the technique of obtaining roentgenographic head film, has matured into an invaluable tool for orthodontic clinical work and research. Cephalograms are currently used to establish skeletal and dental proportions during treatment planning, serially superimpose and evaluate changes brought about by growth and/or treatment, and predict dento-facial changes that might occur in the future.

Although at present cephalometric films are routinely collected and are considered a standard of care in clinical orthodontics, the original technique, as developed and introduced by Broadbent¹¹ in 1931, was for research purposes only. It was intended to study the growth patterns of craniofacial structures by way of superimposing serial radiographs. Hofrath¹², who concurrently developed the same method in Germany and named it “teleroentgenography”, saw another application and proposed that it be used in clinical practice for planning and following operative procedures.

From its inception, cephalometry was intended to be a three-dimensional enterprise. The method developed by Broadbent and Bolton involved taking two head films, one in lateral projection, lateral cephalogram or norma lateralis, and another in frontal projection, posterior-anterior cephalogram or norma frontalis. The two films were taken using a specially developed cephalostat, with two x-ray sources positioned at 90 degrees

to each other, while the Frankfort horizontal reference line was kept parallel to the floor. The stereo-pair of films was to be placed into one plane by “unfolding” the films along the corner at which the two cone-shaped x-ray beams approached each other. They could also be orientated one to the other by the use of an “orientator”, a special acetate overlay that allowed connecting identical landmarks from the lateral to the PA film.¹³

Thus, from the beginning, the PA film was a constitutional and essential element of cephalometry. However, it soon became apparent that three-dimensional cephalometry, although conceptually accurate, was not reliable in practice.¹⁴ The reasons for this were the following:

1. In order to reliably locate stereo-pairs of landmarks, the same landmark has to be located on each film and with an acceptable degree of accuracy. However, the images of most anatomic structures on which these landmarks are located differ in shape and discernibility between the lateral and PA cephalogram. Consequently, it can not be expected that the exact same landmark will be located on each film.
2. The second problem involves the differential enlargement factor between the two films. Given a constant film-focus distance the enlargement factor for all structures lying any given perpendicular distance from the film plane is the same. Conversely, if two structures are at a different distance the enlargement factor for any given anatomic landmark will differ between the lateral and the PA film, unless by coincidence the structure happens to be at the same distance from both films. The same principle applies to the vertical position of each landmark on either film. Unless the landmark has the same vertical position on both films the enlargement factor will be different. Therefore,

there is no way of relating the observed images of the same landmark on the two films of a Broadbent stereopair.

This realization contributed to the abandonment of the idea of three-dimensional representation of the head. Since most patients encountered by orthodontists were symmetric or within an acceptable range of asymmetry the need for PA cephalograms sharply diminished. It seemed appropriate to focus on anterior-posterior relationships, which could readily be recorded from lateral cephalograms. Over time, the cephalometric units were modified, so that instead of having two x-ray sources at 90 degrees to each other, as originally constructed by Broadbent and Bolton, only one x-ray source is now being used. In contemporary use, the patient is rotated 90 degrees in order to obtain a PA cephalogram.

However, advancements in orthodontics revived the need for PA cephalograms. The perceived value of the PA film grew with the development of techniques for palatal widening and maxillary orthopedics. Also, an increased awareness of the relationship between respiration and growth created a need for assessment of transverse dento-skeletal dimensions.¹⁵ Evaluation of dental and skeletal asymmetry also became an important factor in orthodontic treatment planning and diagnosis as orthodontics evolved to include dentofacial orthopedics. The postero-anterior cephalogram was the only cephalometric view that could show the width and angulation of the maxillary and mandibular dental arches, their relation to their respective dentoalveoli, the skeletal bases of the maxilla and mandible in transverse and vertical plane of space, and their relationship to the rest of the cranial bones. In addition, it revealed the size of the nasal

-cavity and deviations of the nasal septum. The relative vertical dimensions of bilateral osseous structures could also be assessed.¹ Since the PA cephalogram accommodated the right and left sides at a relatively equal distance from the film and source, asymmetries in vertical and transverse proportions could be located and quantified by comparison of the sides.

At present, PA cephalograms are not routinely used in orthodontic practice. Most often the decision to order PA film is based on clinical findings which include obvious dentofacial and skeletal asymmetries, dental midline discrepancies and presence of posterior crossbites. Other reasons include evaluation of maxillary anatomy because of suspected airway restriction, and signs and symptoms of TMJ pathology. Studies by Atchison et al.¹⁶ and Tyndall et al.¹⁷ suggested there is a difference in PA film ordering practices between orthodontic private practitioners and educators, with a greater percentage of educators ordering these films. Luke et al.¹⁸ conducted a study that examined the rationale for ordering PA films among orthodontic residents and found that there was no standardized protocol for ordering these films, but the PA requisition pattern depended on previous exposure to experienced orthodontists and educators in the residents' career.

1.6.2 Craniofacial Asymmetries and their Relevance in the Treatment of Orthodontic Patients

By definition, symmetry indicates equality in form and size of parts distributed around a center of an axis, at two extremes or poles, or on the opposite sides of the body. However, such symmetry is applicable to the living being only to a limited extent. The human body, just like all mammals, exhibits decided differences in size, form and distribution of organs between the right and left sides.¹⁹ Humans exhibit not only anatomical but also functional departures from ideal symmetry. For instance, behavioural asymmetry is well illustrated by handedness. About 90% of the population are right handed while only 10% are left-handed. Preference for using one eye or one leg for performing specific activities is also evident.²⁰ There are reports that indicate craniofacial asymmetry could be related to hand dominance.²¹

Asymmetry of the face has been recognized as early as the times of ancient Greece. Hasse's investigations²² of Greek statuary clearly showed that the artists incorporated a range of asymmetries in the faces carved in stone. Craniofacial asymmetry can be categorized as mild, moderate, or severe.²³ The distinction between these categories is largely based on subjective opinion because objective standards for classification do not exist. Mild facial asymmetries result from minor displacements of the maxilla and/or mandible in the vertical or transverse plane, or variations in size between the right and left halves of the skeletal structures or the overlying soft tissues. A minor degree of facial asymmetry seems to be not only trivial but also a desirable variation of the craniofacial structures. Peck et al.²⁴ studied the facial proportions of 52 professional models, beauty contest winners, and performing stars and found measurable asymmetry in all individuals.

Zaidel et al.²⁵ found that we seem to experience absolute facial symmetry as aesthetically displeasing. The author also reported that we have an affinity to perceive one facial side as more attractive than the other. A systematic asymmetry between various craniofacial regions within healthy individuals could not be demonstrated,²⁶ which indicates that in healthy subjects an overall visual balance is created despite the presence of asymmetry in particular craniofacial regions.

Facial asymmetry increases from cranial to lower face structures. In a retrospective survey of 1460 orthodontic / orthognathic patients, conducted at the University of South Carolina, 34 % were found to have clinically apparent facial asymmetry.²⁷ Out of these, 5% involved the upper face, 36 % the midface, and 74% the chin. A cranio-caudal gradient of asymmetry has also been documented in a population with normal occlusion and balanced facial proportions.²⁴

Although the literature agrees that facial asymmetry exists in individuals with normal facial appearance^{19, 26, 28-35} the reports regarding side predominance are contradictory. Larger left side has been found in several reports,²⁸⁻³¹ but other authors have reported larger right side.^{24,26,32,33} There is some evidence that asymmetry of the craniofacial complex may be age related, with greater facial asymmetry in childhood and adolescence.³⁴ Cross sectional studies completed at the University of Toronto in the 1960s have indicated that before 9 years of age the left side of the mandible dominated over the right side. Mandibular asymmetry has also been found to fluctuate in magnitude with increasing age.^{34, 36}

Facial asymmetry during childhood and adolescence might be related to gender.²⁶ In boys, relative maximum side differences decrease while in girls increase with age, but overall more boys than girls show asymmetries. Mandibular asymmetry follows this trend. It has been found significantly larger in boys at a younger age, however, by 16 years of age the gender difference diminishes.³⁴ In adult population no gender-associated differences of craniofacial asymmetry have been reported.^{31,33}

Numerous etiologic factors including both genetic and environmental influences can cause craniofacial asymmetries.¹⁹ The etiology of some of the more severe asymmetries is better understood, such as the one observed in individuals with craniofacial syndromes. These include hemifacial microsomia, retinoic acid and talidomide teratology, clefting syndromes and the craniosynostoses. Cohen^{20, 37-41} stated that clinically significant asymmetry is etiologically and pathogenetically diverse and may be localized or generalized. He reviewed the well-known causes of asymmetry under the following seven categories:

1. Gene mutations

In favor of genetic etiology of somatic asymmetry are experiments with rat embryos. A mutant disorganization gene on chromosome 14 in the rat resulted in variety of developmental anomalies in structures derived from all three germ layers and asymmetric expression was common.⁴² In contrast, Mulick³⁵ using the serial twin-study method could not prove a strong genetic influence on craniofacial asymmetry and concluded that unfavourable external factors play a large role in the creation of craniofacial asymmetry.

2. Embryopathies, including malformations and disruptions

Malformations are a result of an intrinsically abnormal developmental process that leads

to a morphologic defect of an organ. Cleft lip and palate belong to this category. Clefts of the lip and palate are twice as common on the left side and to date the reason for such preferential laterality remains unknown.

3. Fetopathies, including deformations

Mandibular asymmetry in the newborn period is an example of deformation as a result of lateroflexed position of the head of the foetus with the shoulder pressed against the mandible for a long time during late intrauterine life.

4. Hemi-asymmetries, including hemihyperplasia, hemihypoplasia and hemiatrophy

These conditions can affect either one tissue, such as bone, or multiple tissues including soft tissues, muscles and cartilage. Mandibular hemihypertrophy could be caused by true prognathism with increased unilateral growth, unilaterally enlarged condyle with no enlargement of the ramus or body, or true mandibular hemihyperplasia in which there is enlargement of the mandible on one side including condylar head, neck, ramus and body.

Hemifacial microsomia is a well-known hemihypoplasia. The etiology of this syndrome is not clearly understood, although disruption of vascular supply with subsequent haemorrhage in the first branchial arch has been suggested.⁴⁴ Romberg syndrome is the quintessential craniofacial disorder characterized by hemiatrophy. The condition usually begins in the first decade of life and spreads slowly but progressively to involve the soft tissues, muscle, cartilage and underlying bone. There is a marked predilection for left-sided involvement. Alterations in the peripheral sympathetic system have been implicated in the etiology of this condition.⁴⁴

5. Craniosynostoses

In plagiocephaly, or unilateral premature synostosis of the coronal suture, the midface

shift towards the affected side, and the mandible grows towards the opposite side.⁴⁵

Apert syndrome is also characterized by craniofacial asymmetry, while the other well-known craniosynostosis, Crouzon syndrome, is not. Genes responsible for these deformations have been mapped on specific chromosomes.

6. Hamartroses

The hamartroses are a large group of disorders with a propensity to develop neoplasms. They are usually with autosomal dominant inheritance but can be of sporadic occurrence as well. Some examples include Sturge-Weber angiomatosis, neurofibromatosis, nevoid basal cell carcinoma syndrome, and Gardner syndrome. All conditions present with a variety of lesions with asymmetric distribution.

7. Various common and well-known factors

These include tumors, cysts, infections, inflammations, acute and chronic traumas and other conditions involving the craniofacial hard and soft tissues. Infections as factors in the etiology of TMJ ankylosis and subsequent growth deformity are rare, since they have been reduced to minimum by timely and appropriate medical treatment. Rheumatoid arthritis in childhood may affect the TMJ-s unilaterally or bilaterally, leading to considerable destruction of the growth tissues.^{8, 46} Arthritis associated with systemic conditions such as psoriasis can also have monoarticular presentation and result in significant craniofacial asymmetry.

Patients with congenital muscular torticollis, a pathologic condition characterized by a unilateral shortening of at least one cervical muscle usually the sternocleidomastoid, and patients with postural scoliosis have been described as possessing progressive facial asymmetry.⁴⁵ At one time it was thought that fractures of the mandibular condyle can

lead to distortion of mandibular growth in proportion to the time of injury, and as a result of diminished condylar growth on the affected side. However, Proffitt et al.⁴⁷ point out that many patients with condylar fractures can continue to have normal growth and development. Following a fracture, if occlusion is restored and normal function continues, the fibrocartilage of the condyle will regenerate and the position of the mandible will be maintained. It has been suggested that only those patients that have limited function due to intracapsular haemorrhage and resulting ankylosis will develop significant mandibular deformity. In addition, secondary deformities may include tilting of the occlusal plane and disturbed maxillary growth.⁴⁵ There are also reports of compensatory overgrowth of fractured condyles⁷ by a mechanism that is not well understood but could be related to the overgrowth of bony tissue following fracture of a long bone which has been well-documented in the orthopedic literature. Trpkova et al.⁴⁸ reported that female adolescent patients with bilateral TMJ disc displacement have significantly greater vertical asymmetry mainly due to decrease in facial height on the right side.

Kovero et al.²¹ found that chronic pressure of sufficient duration, such as prolonged violin playing, can cause dentofacial alterations in children. The reported changes included increased ramal height and increased facial height on the right side (the side opposite from the one the violin is held against) and overall greater facial asymmetry with right side dominance than controls.

Dental Asymmetries

Mild asymmetries within the dental arches are common and usually do not cause

functional problems to the orthodontic patient.⁴⁹ Dental asymmetries can be found when the mesio-distal crown diameters are compared between analogous teeth on the right and left sides. Tooth size asymmetry usually doesn't involve an entire side of the arch. However, a common finding is that teeth in the same morphological class will tend to have the same direction of asymmetry. For instance, if there is one larger premolar the chances are high that the other premolar on the same side will be larger, but the molars will not follow the trend.⁵⁰ Epidemiological studies indicate that sagittal molar asymmetry can be found in 23% to 30% of untreated children, while non-coincident midlines can be found in 21%. Among orthodontically treated patients the most common asymmetry was mandibular midline deviation (62% of patients), with reported lack of dental midline coincidence in 46%, maxillary midline deviation in 39% and molar classification asymmetry in 22%.⁴⁴

Studies that have evaluated the relationship between occlusion and skeletal asymmetry have corroborated contradictory results. Reports that there is no relationship at all have been done mainly on samples that included various and non-specified malocclusions.^{31,52} In contrast, it is well documented that individuals with cross-bites due to mandibular shift are at risk to develop more severe mandibular asymmetry than those with normal occlusions,⁵³ making the presence of cross-bites one of the best-recognized needs for early intervention.⁴⁹ There are reports that in adults with crossbites the mandible is not necessarily more asymmetric but rotated towards the side of the cross bite, with reported asymmetry in the position of the glenoid fossa.⁵⁴ One of the more challenging malocclusions to treat orthodontically, the Class II subdivision, is caused by a combination of dental and skeletal factors. Both asymmetric condylar position and A-P

molar asymmetry have been identified as significant factors that contribute to the development of CI II subdivision malocclusion.⁵⁴⁻⁵⁹

Padwa et al.⁵⁶ examined the cant of the occlusal plane as a reflection of frontal asymmetry. They included both dental professionals and lay people as observers in a study on 188 orthognathic patients and found that a cant of the occlusal plane relative to a horizontal reference line of 3 degrees was recognized as abnormal by 50% of the observers, while cant of 4 degrees was obvious to 90% of the observers. There were no statistically significant differences between the evaluations of trained and untrained observers. Kokich et al.⁵⁷ however, did find significant discrepancies in the perception of anterior dental asymmetries between orthodontists, dentists and lay people. Orthodontists detected a cant of the incisal plane at 1 mm while lay people detected it at 3 mm. Surprisingly, a maxillary midline asymmetry was judged as unesthetic at 4-mm deviation by orthodontists, while lay people did not rate it as unesthetic even at 4 mm.

In view of the above discussion, a most significant consideration in the orthodontic treatment planning is whether the patients exhibit a degree of asymmetry that exceeds their functional adaptability and facial harmony. Although orthodontists are trained to assess patients for presence of dental and skeletal asymmetries, this is not always an easy task. Diagnosing an asymmetric dental condition can be simple such as the presence of dental midline deviation, asymmetric dental crowding or spacing. However, other times an underlying skeletal asymmetry can be masked by dental compensations, and will reveal itself during the course of orthodontic treatment. A number of other compensatory mechanisms take place, such as tilting of the head, mandibular posturing, soft tissue

compensations, that make the identification of asymmetry by clinical examination at times impossible.

From an orthodontic point of view, it is important to know whether an observed asymmetry is skeletal, dental, functional or any combination of these.⁵⁰ Based on the location and the severity of the asymmetry, treatment can range from orthodontic correction of the dental asymmetry with the use of asymmetric orthodontic forces or asymmetric pattern of extractions, to combination of orthodontic and orthognathic treatment, along with prosthodontic or other dental restorative work. As Thompson⁵⁸ stated in 1943, “ malocclusion is not a cause of asymmetry of the face, but rather is one of the symptoms. The orthodontic treatment may straighten the teeth, but it will not straighten the face”. Reyneke et al.⁵⁹ presented a simple classification that addressed the aesthetic and structural discrepancies of dentofacial asymmetries irrespective of cause. Their rationale was that orthodontic and surgical correction of the maxillo-mandibular complex would not differ appreciably for etiologically different asymmetries with similar clinical presentations for as long as growth is not a contributing factor.

While facial examination, dental casts, and deprogramming intraoral appliances can help determine dental, soft tissue, and functional asymmetries, the PA cephalogram remains the only available tool that can reveal the extent of skeletal asymmetry, both in the vertical and transverse dimension.

1.6.3 The Posterior-anterior (PA) Cephalogram- Radiographic Technique and Inherent Errors

A cephalogram is a two-dimensional representation of a three-dimensional structure. Inevitably, in the process of acquisition of the image some information is lost. Ahlqvist et al.⁶⁰ astutely pointed out that in all conventional radiographic systems where a fixed focal spot and a fixed film are employed in radiographing a non-movable object only in the ideal case a true orthogonal projection is created. The important questions that need to be addressed are not if there are inherent errors, but how large these errors are and whether the created image conveys information that is clinically useful.

As with any radiographic technique, the cephalometric process begins with the x-ray exposure and ends with the evaluation and diagnosis in the hands of the orthodontist. Between these operations, a series of problems arise. Some are shared between the lateral and PA cephalogram, while others are characteristic for the PA cephalogram.

There are two major categories of errors associated with cephalometry, technical problems and analytical problems.

1. Technical problems

Technical difficulties associated with PA cephalometry arise from three sources:⁵

- 1a. The set-up of the cephalometric equipment
- 1b. The positioning of the patient in the cephalostat
- 1c. The quality and speed of the film and the additional use of collimators and intensifying screens in order to reduce patient-irradiation dose

The set up of the cephalometric equipment creates three types of problems:

- magnification
- distortion
- penumbra

In radiography, the x-rays travel from a small source (point of origin) towards the film, along a straight but diverging line, with the patient placed a certain distance between the source and the film. Naturally, this geometry of the radiographic set-up creates an enlarged image. Schwartz ⁶¹ was the first to recognize the unique problems of frontal magnification and used Cartesian reference system of coordinates and solid geometric principles in describing a method of compensation. Bergerson ⁶² also studied this problem and provided compensation tables with enlargement factors for distances measured from lateral and frontal cephalograms. Frontal cephalometric compensation was calculated using the A-P distance of the landmarks from the midporionic plane as measured from the lateral cephalogram. He found that variations in enlargement in the frontal film can range between 0.3% to 9.2 %. These compensation factors are valid under the assumption that all other factors, such as alignment of the cephalometric equipment, film and patient positioning are ideal.

Adams ⁶³ provided the following proportion to express the geometry of the radiographic set-up:

Distance Source-to-Object/ Distance Source-to- Film = Size of object / Size of image

From this relation it can be calculated that the size of the image is proportional to the size of the object and the source-film distance, and inversely proportional to the source-object distance.

Size of image = (Size of object) x (Distance Source-to-film)/ (Distance Source -to-object)

It follows that in order to reduce magnification two factors can be controlled, the source-film and the source-object distances. The distance between the x-ray source and the object should be as large as possible, while the distance between the object and the film should be as small as possible. However, there are some practical limitations to these rules. The concentration of penetrating x-rays decreases inversely with the square of the distance from the source to the object. When it is increased beyond five feet, the decrease in magnification is accompanied by a sharp increase in patient irradiation.⁶² For this reason, the North American standard for source-film distance remains set at 5 feet, as in the original Broadbent cephalometer.

A universal standard for film-object distance in PA cephalometry has not yet been established, despite a well-recognized need for serial films or exchange of radiographs between orthodontic practitioners and researchers. The current standard for taking PA cephalogram is with the film cassette as close to the patient as the head size will allow, with the patient's nose touching the cassette. Ghafari et al.⁶⁴ used human dry skulls to evaluate the effect of various object-film distances on transverse measurements and didn't find any significant differences within a range of 11 to 14 cm. Therefore, the authors

proposed that 13 cm (measured from the interporionic axis to the film) could be adopted as a standard in PA cephalometry. As a practical standard on human beings this measure may not always be appropriate, as is the case of the patient with a larger nose. The distance porion-film may need to be increased to 14 or more. The increase in magnification at this distance should not significantly change transverse skeletal measurements, while the change in vertical measurements was not reported.

Distortion is very closely associated with magnification, but is a distinct problem in cephalometrics. Distortion is inaccurate duplication of a structure, while enlargement is accurate proportional expansion of a structure.⁶² Distortion occurs in several different ways. Since magnification is a factor of the distance between the film and the imaged structures, any time a three-dimensional structure is exposed, a differential amount of enlargement will occur for different parts of that structure. It follows that structures within the same skull will not be only enlarged but also “misrepresented” or distorted. These distortions are small but nevertheless present. Another type of distortion has been termed radial displacement by Adams.⁶³ He stated that all peripheral structures i.e. those farther from the path of the central x-ray beam are subject to greater enlargement than centrally located structures. Yet another type of distortion is produced by rotations of the head in the cephalostat, which are most difficult to anticipate and compensate for. Similar to these distortions are those produced by asymmetry between parts in the human skull. Distortion also occurs when the divergent x-rays form tangents to rounded surfaces that are on the source side of the midsagittal plane (in lateral cephalograms) or midporionic coronal plane (in frontal radiographs).⁶²

It should be pointed out that most studies that have evaluated errors related to cephalometry are in agreement that errors due to projection are small relative to errors involved with landmark identification.^{3,65}

Penumbra or optical blurring occurs as a result of the object being exposed by x-rays from all areas of the source. This mix of x-rays with diversified paths creates blurred contours of the image. Penumbra is also directly proportional with the distance between the head of the patient and the film, and inversely proportional with the distance between the focal spot and the film. With most current cephalometric units, the size of the penumbra is generally small. It has been measured to be less than 0.2 mm⁶⁶ or between 0.3 and 0.4 mm.⁶⁷

Cephalostats facilitate the production of standardized cephalometric images. Nevertheless, positioning the patient in the cephalostat gives rise to another set of errors. Firstly, standards for head placement for PA exposure have not been established to date. Various protocols described in the literature include head depressed (with forehead and nose against cassette), head slightly depressed, natural head position, or Frankfort horizontal parallel to the floor.^{15, 63, 68-71} Secondly, PA cephalograms are more prone to positioning errors than lateral cephalograms simply because the cephalostat allows more freedom of movement around the midporionic axis.⁵ Following the rules of geometry, rotations around transverse axis will affect vertical measurements while rotations around vertical axis will affect transverse measurements. Investigations of the extent of movement that would have to occur in order to significantly influence measurements have shown that 5 degrees around either axis produce little change in landmark location compared with “neutral” or non-

rotated head position.⁵ Ghafary et al.⁷¹ examined the effects of rotations within 10 degrees around transverse axis (5 degrees up and down rotations) and reported no significant differences between maxillary and mandibular transverse measurements taken at neutral and rotated positions. These data are comparable to Ahlqvist et al.⁷² who examined the effects of head rotations and translations on measurements from lateral cephalograms and found that +/- 10 mm of translation did not substantially increase the error of measurements. Rotations of +/- 5 degrees from the ideal position resulted in errors that were less than 1 %, however, the error increased sharply when the increase of head rotation exceeded 5 degrees, even at rotations of few degrees over 5 degrees. Pirttiniemi et al.⁷³ evaluated the effect of normal variation in head posture in a cephalostat between repeated recordings and its effect on geometric errors in PA cephalometry. They used a modification of the three-dimensional roentgenographic method developed by Eliason et al.⁷⁴ and Ahlqvist et al.⁷² involving a computer-aided design program (CAD). A series of dry skulls was used to obtain PA and lateral cephalograms and to define various points in three-dimensional space by x, y and z coordinates. All points were then manipulated artificially with the use of the CAD program to calculate the effects of rotating the head around a vertical axis passing through the left ear rod. The geometric error was measured as the absolute change in the distance of the lateral coordinate of each point to the skull midline. The lowest error was measured for landmarks located near the midsagittal plane while the largest error was recorded for points located farthest from the midsagittal plane. These studies support the use of PA cephalogram provided due care is taken when placing the patient in the cephalometric machine.

Factors related to the actual conversion of the x-ray exposure into an image on the film can be controlled by the use of collimators to reduce scatter and secondary irradiation.

The extended length of the tube or prepatient blocking offer the dual benefit of reducing patient exposure and increasing image quality. Other means of reducing patient radiation are rare earth intensifying screens and fast films. Studies have been performed to assess the effect of the use of these exposure-reducing devices on image quality and discernability of anatomic structures on the film. The conclusions of these studies have been that image quality may be slightly decreased by their use, however, the diagnostic value of the film is not significantly changed.

2. Analytical problems

Analytical problems can occur during the following steps:

2a. Tracing or digitizing the image

2b. Locating landmarks

2c. Performing an analysis and obtaining measurements

There are three ways to obtain a reading of a cephalometric image in contemporary cephalometry. One method is manually tracing and locating landmarks with the use of hand instruments to perform an analysis. Another is manual tracing of the image and using a computer to locate landmarks on the tracing, and the third is direct digitization of the radiograph without prior tracing. Tracing of a cephalometric image involves errors that arise from the instruments used in the process. These include the thickness of the pencil lead and the accuracy of the observer's eye.⁵ Any imperfections of the instruments used to measure distances and angles also add to the total error of the analysis. The computer-aided digitization eliminates the conventional instrumentation error, but inevitably the observer-related error remains incorporated in the total error. Studies that

have evaluated the effect of tracing vs. digitization have provided evidence that error due to tracing is negligible compared with errors due to landmark identification.^{3, 65} Comparisons of errors introduced by any of the three methods have revealed that direct digitization was more reproducible⁷⁵ but there were no significant differences between the three techniques.⁷⁶ Traditional hand measurements compared well with computer based methods. It has been recommended that for purposes of convenience digitization be used as a faster and more efficient way of locating landmarks.^{75,76}

Accurate identification of cephalometric landmarks depends on a number of factors, including density and sharpness of the radiographic image, anatomic complexity and superimposition of hard and soft tissues, observers' experience when locating a particular landmark and the precise definition of landmarks' location. There are two factors to consider regarding landmark location. First is landmark validity, or the extent to which, in the absence of measurement error, the value obtained represents the anatomic structure of interest. Second is landmark reproducibility, or the consistency with which a landmark can be identified on repeated occasions.³ Landmark identification error is generally larger when more than one observer is involved in the analysis despite a prior consensus on landmark definition and location.¹ Houston³ discussed methods of controlling errors in cephalometric analysis. Measurements should be checked for "wild" values either against previously published standards or against measurements of the study itself. For this purpose cephalometric tracings should be replicated and re-measured on several occasions which would help determine the variability of the landmark-locating error. This error variance is a measure of landmark identification error and should be a small proportion of the total variance of error.³

Studies on reproducibility of landmark location from lateral cephalograms have reported that each landmark demonstrates its own envelope of error, characterized by magnitude and distribution along the horizontal and vertical axes.³ Therefore, it has been suggested that the choice of landmarks used in a cephalometric analysis should be guided by the specific objective of the analysis. As a general rule, landmarks with large horizontal identification error should be avoided for transverse measurements, while landmarks with large vertical error should not be used for measuring vertical dimensions.¹

There are only two studies in the literature that have evaluated landmark identification error on PA cephalograms. El Mangoury et al.⁴ studied the reproducibility of thirteen landmarks on the PA image. They used PA cephalograms of real patients and only one observer was involved in locating the landmarks. In this study dental landmarks were found less reliable than skeletal landmarks. The range of mean error in the x coordinate was 0.39 to 1.74 mm, and 0.27 to 1.25mm in the y coordinate. Major et al.¹ determined the reproducibility of 52 landmarks on PA cephalograms of real patients and dry skulls. Comparisons were also made between the range of error when one observer was involved as opposed to four. The range of error was significantly larger when four observers were involved, (0.31 mm to 4.79 mm), a difference attributed to interpretative variation between the four observers. It was also found that landmark identification error was larger for some landmarks when data were measured on dry skulls as opposed to patients. Based on the results of this study it was concluded that many landmarks used in PA cephalometrics have an unacceptable magnitude of error.

A study by Pirttiniemi et al.⁷³ is the only published source of information on the accuracy of landmark location on PA cephalograms. In this study landmarks were located on PA cephalograms of dry skulls first without markers, and the second time with metal markers glued onto the skulls. Results revealed that dental landmarks (maxillary and mandibular incisors midlines) and point pogonion were most accurately located. Condylar points and fronto-zygomatic suture points showed significant error and the authors discouraged the general use of these landmarks.

1.6.4 Cephalometric Analysis of Asymmetry

Cephalometric images are used in orthodontic and orthognathic surgical planning for detailed measurment of dimensions and relationships within the facial bones and skull. Various frontal cephalometric analyses have been used for several decades. Some have been developed primarily for surgical use ^{59, 77-79} while others have been refined for orthodontic purposes. ^{8, 10, 15, 28-32, 52} Although the number of proposed PA cephalometric analysis is large each one has its own limitations, and not one has been proven superior to others. ⁵ Often the objective of the investigation determines the choice of analysis. Linear measurements of vertical and transverse dimensions can be obtained from the PA cephalogram relative to chosen reference planes or between certain anatomic landmarks. In addition, angular measurements and ratios can be calculated, as a way of eliminating the effects of head size and differential magnification. ¹⁰

When the primary use of the PA cephalogram is measurement of asymmetry, the first crucial step in the analysis is the choice of reference lines. In order to measure vertical and transverse asymmetry, a horizontal and a vertical reference line are required. Structures to be used as reference points should be stable, should have a high degree of reproducibility and a high degree of symmetry. In the ideal case an analysis of asymmetry should be performed from a line that divides the cranium in two perfect halves. As previously reviewed, scientific evidence suggests that this line is a theoretical entity rather than a realistic one, given the inevitable asymmetry that exists in every individual.

A literature review revealed the following three major methods for measuring asymmetry:

1. Anatomic method

A horizontal line connecting bilateral landmarks is drawn and a vertical line perpendicular to the horizontal reference and passing through an anatomical structure is constructed to represent the craniofacial axis. Landmarks that are in the proximity of the cranial base, such as zygomatico-frontal sutures and crista galli have often been used.⁶ The anterior cranial base completes its growth earlier than the rest of the face and offers the stability required from a reference structure. From a region of relative stability, the evaluation of other growing areas of the face can be made.⁸⁰ For an asymmetry analysis, the reference system should also offer relative symmetry. The upper and middle face, including the forehead and orbits, as well as the anterior cranial base are the most symmetric regions.^{30, 32} Orbital landmarks have been used frequently in the construction of a horizontal reference line. The validity of the superior and lateral orbital contours as stable reference areas after eight years of age have been established.⁹ The superiormost points of the orbits also have an acceptable identification error.¹ Lund⁷, Stabrun⁸, Alavi⁹ have used the superiormost point of the orbital outlines to construct the horizontal reference line.

Grummons et al.¹⁰ developed a PA analysis to provide information about specific locations and amounts of facial asymmetry. They used several horizontal reference lines located in different regions of the face to measure vertical relationships. Transverse relationships were measured to a vertical reference line constructed between crista galli and anterior nasal spine. In cases when these landmarks can not be properly identified the authors proposed using alternate vertical reference lines, constructed between zygomatico-frontal points or the centers of the right and left foramen rotundum. Cheney⁸¹ used a vertical line that passes through nasion and anterior nasal spine. Sassouni^{82, 83}

presented a method by which five horizontal lines were drawn between the supra-orbital, latero-orbital, bi-zygomatic, bi-mastoid and bi-gonial points. In an ideal situation these lines should be parallel, and a perpendicular to these lines should represent the facial midline.

2. Best-fit method

This method is a modification of the anatomic approach. Crista galli, nasion, and zygomatico-frontal sutures anatomically fulfil the criteria for symmetry and stability, however, these landmarks are difficult to identify and also have inadequate reproducibility along the vertical axis.¹ Another drawback of the anatomic method is that the choice of any reference point introduces bias from the outset and determines the outcome of the entire subsequent analysis. A geometric approach could be used to overcome these problems. Multiple pairs of bilateral landmarks are located, joined with horizontal lines and then bisected. A vertical reference line is then constructed as a best fit line for all the midpoints.^{28, 29, 31} This method allows for an adjustment in the case of a structure with obvious asymmetry. When multiple pairs are chosen, if a midpoint is obviously off in relation to the other midpoints of the cranium and face, it can be excluded when drawing the axis. Vig and Hewitt²⁸ further modified this method. They drew a best-fit line through points that represented the maxillary region and another line of best-fit through points in the mandibular region. The angle between the two lines was a measure of asymmetry between the two facial regions. In this investigation the mandibular axis was found to deviate to the left of the maxillary axis in 88% of the children examined.

The best-fit approach relies on the accurate identification of multiple landmarks, which

decreases bias and the risk for error. However, the best fit line accommodates anatomic landmarks of both upper and lower craniofacial structures and there is a potential that asymmetry of a particular craniofacial region may not be detected since the best-fit line “centers” all components and minimizes asymmetry.

Johnston ⁵ examined the deviation of various reference lines drawn between anatomic points located on the PA cephalogram. He tested a series of horizontal and vertical reference lines against a constructed best-fit horizontal and best-fit vertical line. Based on the results, he proposed that the intersection of the superior border of the greater wing of the sphenoid bone with the lateral orbital margin be used for construction of a horizontal reference line. The landmarks most appropriate for determining vertical reference line were the bisector of the line through the intersection of the inferior border of the sphenoid bone and the lateral orbital margin, and the midpoint of the nasal septum. In this study it was assumed that the best-fit line represents the most adequate reference line for measuring asymmetry. Johnson also pointed that the vertical and the horizontal best fit line are not necessarily perpendicular to each other and that they should be constructed independently.

3. Triangulation method

This method was originally developed to avoid the use of reference lines that may be difficult to construct and also introduce bias. Following identification of bilateral and midline points on the radiograph, various triangles are constructed on the right and left sides. Several modifications of this approach have been published in the literature. Shah and Joshi ³² constructed triangles to represent the cranial base, lateral maxillary region,

upper maxillary, middle maxillary and lower maxillary region, dental region and mandibular region. They compared the size of each pair of triangles to provide a measure of asymmetry. If symmetry exists, the triangles should have equal surface area and shape.^{28, 29,32,77, 84} Grummons and Kappeyne¹⁰ also used this method to evaluate mandibular asymmetry by constructing left and right triangles formed by connecting the heads of the condylar processes, the antegonial notches and menton. The second triangulation method used by Butow and Wan der Walt⁷⁷ also requires construction of triangles but utilizes a vertical reference line to bisect the triangles into halves and then compare the surface areas of each pair of triangles. For instance, a maxillary triangle is formed by crista galli, left and right jugal point and bisected by the facial axis. Grummons and Kappeyne¹⁰ constructed a maxillary and mandibular triangle by drawing perpendicular connectors from each jugal point and antegonion onto the midfacial axis and connecting lines to crista galli. This method can quickly and effectively reveal the presence of asymmetry of the different component areas of the craniofacial complex but further linear analysis will be needed to discover the exact measure that contributes to the asymmetry. It also relies on the construction of a vertical line that represents the facial midline.

In summary, when mandibular and maxillary size, position or asymmetry is in question, it is essential to use a system of reference lines drawn upon stable, reproducible, and easily identifiable structures. In addition, if longitudinal evaluations are to be done, the reference lines should be constructed in areas that will not appreciably change during the course of orthodontic treatment or as a result of growth.⁵ This indicates that maxillary and in particular mandibular landmarks, as well as dental landmarks, should not be used in the construction of reference lines. In this way, the observed values are more likely to

represent the mandibular and maxillary structures in a meaningful and objective way.

Most authors that have published PA analysis have relied both on available scientific evidence and personal bias in their choice of reference lines. Although the literature suggests that a best-fit line may be the most appropriate reference to use, so far there is no evidence that a best-fit line is the most accurate line to use in an asymmetry analysis.

References

1. Major PW, Johnson DE, Hesse KL, Glover KE. Landmark identification error in posterior- anterior cephalometrics. *Angle Orthod* 1994;64:447-54.
2. Major PW, Johnson DE, Hesse KL, Glover KE. Effect of head rotation on posterior-anterior cephalometric landmark identification. *Angle Orthod* 1996;66:51-60.
3. Houston WJB. The analysis of errors in orthodontic measurements. *Am J Orthod* 1983;83:382-90.
4. El Mangoury NH, Shaheen SI, Mostafa YA. Landmark identification in computerized posteroanterior cephalometrics. *Am J Ortho Dentofac Orthop* 1987;91:57-61.
5. Johnston DE. The posteroanterior cephalometric radiograph. Masters Thesis 1991:pp 46.
6. Harvold EP, Trugue M, Vilorio JO. Establishing the median plane in posteroanterior cephalograms. In: J.A. Salzmann , Ed. *Roentgenographic Cephalometrics 2nd editors*. Philadelphia. J.B. Lippincott Co. 1959. P. 154-60.
7. Lund K. Mandibular growth and remodelling processes after condylar fracture. A longitudinal roentgencephalometric study. Academic dissertation. *Acta Odontol Scand* 1974;32:suppl. 64.
8. Stabrun AE. Mandibular morphology and position in juvenile rheumatoid arthritis. A study on posterior-anterior radiographs. *Europ J Orthod* 1985;7:288-98.
9. Alavi D, BeGole E, Schneider BJ. Facial and dental arch asymmetries in CI II subdivision malocclusion. *Am J Orthod Dentofac Orthop* 1988;93:38-46.

10. Grummons DC, Kappeyne van de Coppelo MA. A Frontal Asymmetry Analysis. JCO 1987;21:448-65.
11. Broadbent BH. A new x-ray technique and its application to orthodontia. Angle Orthod 1931;1:45-66.
12. Hofrath H. Die Bedeutung der roentgenfern-und Abstands aufnahme fur die diagnostik der keiferanomalien. Fortshr Orthodont. 1931;1:232-58.
13. Grayson B, Cutting C, Bookstein FL, Kim H, McCarthy JG. The three-dimensional cephalogram: Theory, technique and clinical application. A J Orthod Dentofac Orthop 1988;94:327-37.
14. Baumrind S, Moffitt FH, Curry S. Three-dimensional x-ray stereometry from coplanar images: A progress report. Am J Orthod 1983;84(4):292-312.
15. Ricketts RM. Perspectives in the clinical application of cephalometrics: the first fifty years. Angle Orthod 1981;51:115-50.
16. Atchison KA, Luke LS, White SC. Contributions of pretreatment radiographs to the orthodontists's decision-making. Oral Surg Oral Med Oral Pathol 1991;71:238-45.
17. Tyndall DA, Turner SP. Radiographic materials, methods and film-ordering patterns among orthodontic educators and private practitioners. Am J Orthod Dentofac Orthop 1990;97:159-67.
18. Luke SL, Lee P, Atchison KA, White SC. Orthodontic residents' indications for use of the lateral TMJ Tomogram and the Posteroanterior Cephalogram. J Dent Educ 1997; 61:29-36.
19. Lundstrom A. Some asymmetries of the dental arches, jaws and skull, and their etiological significance. Am J Orthod 1961;47:81-106.

20. Cohen MM. Perspectives on craniofacial asymmetry. 1. The Biology of asymmetry. *Int J Oral Maxillofac Surg* 1995;24:2-7.
21. Kovero O, Kononen M, Pirinen S. The effect of violin playing on the bony facial structures in adolescents. *Europ J Ortho* 1997;19:369-75.
22. Hasse C. Über Gesichtsasymmetrien. *Arch Anat u Entwicklungsgesch* 1887;11:119-125.
23. Cook JT. Asymmetry of the craniofacial skeleton. *Brit J Orthod* 1980;7:33-8.
24. Peck S, Peck L, Kataja M. Skeletal asymmetry in aesthetically pleasing faces. *Angle Orthod* 1990;61:43-8.
25. Zaidel DW, Chen AC, German C. She is not a beauty even when she smiles: Possible evolutionary basis for a relationship between facial attractiveness and hemispheric specialization. *Neuropsychologia* 1995;33:649-55.
26. Farkas LG, Cheung G. Facial asymmetry in healthy North American Caucasians: An anthropometrical study. *Angle Orthod* 1981;51:70-7.
27. Severt TR, Proffit WR. The prevalence of facial asymmetries in the dentofacial deformities population at the University of North Carolina. *Inter J Adult Orthod Orthogn Surg* 1997; 12:171-6.
28. Vig PS, Hewitt AB. Asymmetry of the human skeleton. *Angle Orthod* 1978;48:141-8.
29. Hewitt AB. A radiographic study of facial asymmetry. *Brit J Orthod* 1974;2:37-40.
30. Letzer GM, Kronman JH. A posteroanterior cephalometric evaluation of craniofacial asymmetry. *Angle Orthod* 1967;37:205-11.

31. Chebib FS, Chamma AM. Incidence of craniofacial asymmetry. *Angle Orthod* 1981;51:214-26.
32. Shah SM, Joshi MR. An assessment of asymmetry in the normal craniofacial complex. *Angle Orthod* 1978;48:141-8.
33. Ferrario VF, Sforza C, Poggio CE, Tartaglia G. Distance from symmetry: A three-dimensional evaluation of facial asymmetry. *J Oral Maxillofac Surg* 1994;52:1126-32.
34. Melnik AK. A cephalometric study of mandibular asymmetry in a longitudinally followed sample of growing children. *Am J Orthod Dentofac Orthop* 1992;101:355-66.
35. Mulick JF. An investigation of craniofacial asymmetry using the serial twin-study method. *Am J Orthod* 1965;51:112-29.
36. Burke PH. Serial observation of asymmetry in the growing face. *Brit J Orthod* 1992;19:273-85.
37. Cohen MM. Perspectives on craniofacial asymmetry. II. Asymmetric embryopathies. *Int J Oral Maxillofac Surg* 1995;24:8-12.
38. Cohen MM. Perspectives on craniofacial asymmetry. III. Common and /or well-known causes of asymmetry. *Int J Oral Maxillofac Surg* 1995;24:127-33.
39. Cohen MM. Perspectives on craniofacial asymmetry. IV. Hemi-asymmetries. *Int J Oral Maxillofac Surg* 1995;24:134-41.
40. Cohen MM. Perspectives on craniofacial asymmetry. V. The cranyosynostoses. *Int J Oral Maxillofac Surg* 1995;24: 191-4.
41. Cohen MM. Perspectives on craniofacial asymmetry. VI. The hamartroses. *Int J Oral Maxillofac Surg* 1995;24: 195-200.

42. Hummel KP. The inheritance and expression of disorganization, an unusual mutation in the mouse. *J Exper Zool* 1958;137:389-423.
43. Poswillo D. Hemorrhage in development of the face. *Birth Defects* 1975;11:61-81.
44. Moss M, Crikelair GF. Progressive facial hemiatrophy following cervical sympathectomy in the rat. *Arch Oral Biol* 1960;1:254-8.
45. Pirttiniemi PM. Associations of mandibular and facial asymmetries-a review. *Am J Orthod Dentofac Orthop* 1994;106:191-200.
46. Stabrun AE, Larheim HM, Hoyeraal HM, Rosler M. Reduced mandibular dimensions and asymmetry in juvenile rheumatoid arthritis. *Arthritis and Rheum* 1988;31:602-11.
47. Proffit WR, Vig WL, Turvey TA. Early fracture of the mandibular condyles: frequently an unsuspected cause of growth disturbances. *Am J Orthod* 1980;78:1-24.
48. Trpkova B, Major PW, Nebbe B, Prasad NGN. Craniofacial asymmetry and Temporomandibular joint internal derangement in female adolescents: A posteroanterior cephalometric study. *Angle Orthod* 2000;70:81-8.
49. Proffit WR, White RP. *Surgical -Orthodontic Treatment*. St. Louis: Mosby; 1990
50. Bishara S, Burkey PS, Kharouf JG. Dental and facial asymmetries: a review. *Angle Orthod* 1994;64:89-98.
51. Sheats RD, McGorray SP, Musmar Q, Wheeler TT, King GJ. Prevalence of orthodontic asymmetries. *Semin Ortho* 1998;4(3):138-45.
52. Shore IL. A cephalometric study of facial asymmetry (Master's Thesis). University of Pittsburgh, 1959.

53. Pirttiniemi P, Kantomaa T, Lahtela P. Relationship between craniofacial and condyle path asymmetry in unilateral posterior cross bite patients. *Eur J Orthod* 1990;12:408-13.
54. O'Byrn BL, Sadowsky C, Schneider B, BeGole E. An evaluation of mandibular asymmetry in adults with unilateral posterior cross-bite. *Am J Orthod Dentofac Orthop* 1995;107:394-400.
55. Rose JM, Sadowsky C, BeGole EA. Mandibular skeletal and dental asymmetry in Class II subdivision malocclusions. *Am J Orthod Dentofac Orthop* 1994;105:489-95.
56. Padwa BL, Kaiser MO, Kaban LB. Occlusal cant in the frontal plane as a reflection of facial asymmetry. *J Oral Maxillofac Surg* 1997;55: 811-6.
57. Kokich VO Jr., Kiyak HA, Shapiro PA. Comparing the perception of dentists and lay people to altered dental esthetics. *J Esthet Dent* 1999;11(6):311-24.
58. Thompson JR. Asymmetry of the face. *J Amer Dent Assoc* 1943;30:1859-71.
59. Reyneke JP, Tsakiris P, Kienle F. A simple classification for surgical treatment planning of maxillomandibular asymmetry. *Brit J Oral Maxillofac Surg* 1997;35:349-51.
60. Ahlqvist J, Eliasson S, Welanders. The cephalographic projection, Part II. Principles of image distortion in cephalography. *Dentomaxillofac Radiol* 1983;12:101-8.
61. Schwartz H. A method of measuring points in space as recorded by the Broadbent-Bolton cephalometric technique. Thesis, Northwestern Univ. 1943.
62. Bergersen EO. Enlargement and distortion in cephalometric radiography: Compensation tables for linear measurements. *Angle Orthod* 1980; 50:230-244.

63. Adams JW. Correction of error in cephalometric roentgenograms. *Angle Orthod* 1940;10:3-13.
64. Ghafari J, Cater PE, Shofer FS. Effect of film-object distance on posteroanterior cephalometric measurements: Suggestions for standardized cephalometric methods. *Am J Orthod Dentofac Orthop* 1995;108:30-7.
65. Baumrind S, Frantz R. The reliability of head film measurements. 1. Landmark identification. *AM J Orthod* 1971;60(2):111-27.
66. Van Aken J. Geometric errors in lateral skull x-ray projections. *Neder T Tand* 1963;70: 18-30.
67. Newman KJ, Meredith HV. Individual growth in skeletal bigonial diameter during the childhood period from 5 to 11 years of age. *A J Anat* 1956: 157-87.
68. Ricketts RM, Roth RH, Chaconas SJ, Schulhof RJ, Engel GA. *Orthodontic Diagnosis and Planning*. Denver: Rocky Mountain Data Systems, 1982.
69. Goaz P, White S. *Oral Radiology*. St. Lous: CV Mosby, 1982.
70. Kalpins RI. A new method for evaluating craniofacial asymmetry utilizing posteroanterior radiography. *J Dent Res* 1985;64:1520 (abst.)
71. Richardson ME. Reproducibility of depressed posterior-anterior cephalometric radiographs. *Angle Orthod* 1967;37:48-51.
72. Ahlqvist J, Eliasson S, Welander U. The effect of projection errors on cephalometric length measurements. *Eur J Ortho* 1986; 8:141-8.
73. Pirttiniemi P, Miettinen J, Kantomaa T. Combined effects of error in frontal-view asymmetry diagnosis. *Europ J Orthod* 1996;18:629-36.
74. Eliasson S, Welander U, Ahlqvist J. The cephalographic projection Part I: General considerations. *Dentomaxillofac Radiol* 1982;11:117-122.

75. Cohen AM. Uncertainty in cephalometrics. *Brit J Orthd* 1984;11:44-48.
76. Sandler PJ. Reproducibility of cephalometric measurements. *Brit J Orthod* 1988;15:105-10.
77. Buttow KW, van der Walt PJ. The “Stellenbosch”-triangle analysis of the postero-anterior and basilar cephalograms. *J Dent Assoc South Africa* 1981;36:461-7.
78. Zwemer TJ, Lorber RM. An annotated atlas of facial analysis. *Dent Clin N Am* 1976;20:641-60.
79. Farkas LG, Bryson W, Klotz J. Is photogrammetry of the face reliable? *Plast Reconstr Surg* 1980;66:346-55.
80. Ranley DM. A Synopsis of Craniofacial Growth. Connecticut: Appleton & Lange, 1988.
81. Cheney EA. Dentofacial asymmetries and their clinical significance. *Am J Orthod* 1961;47:814-29.
82. Sassouni V. The face in five dimensions. West Virginia University, Morgantown, 1960.
83. Sassouni V, Forrest EJ. Orthodontics in Dental Practice. Saint Louis, C.V. Mosby Company, 1971
84. Mongini Mongini F, Schmid W. Treatment of mandibular asymmetries during growth. A longitudinal study. *Europ J Orthod* 1987;9:51-67.

CHAPTER II

FIRST RESEARCH STUDY AND RESULTS

THE VALIDITY OF COMMONLY USED CEPHALOMETRIC LANDMARKS FOR ASSESSMENT OF CHANGES IN POSITION OF DENTO-FACIAL STRUCTURES FROM POSTERIOR-ANTERIOR (PA) CEPHALOGRAMS

2.1 INTRODUCTION

Posterior-anterior (PA) or frontal cephalograms have been used by orthodontic practitioners and researchers for seven decades, albeit with oscillating enthusiasm. From the very inception cephalometry was not only a new method for standardized imaging of cranio-facial structures but also a potential tool for three-dimensional representation of the head. The PA film was an essential element of the new radiographic technique.¹ Broadbent's original cephalostat was set-up to concomitantly take a lateral and a frontal film, which was made possible through the use of two radiographic sources positioned at 90 degrees to each other.

However, three-dimensional cephalometry through the use of cephalometric stereo-pair of films proved to be unreliable in practice.² Disparate differences in enlargement factors as well as various degrees of radiographic distortion between the lateral and frontal film have posed insurmountable problems in the clinical application of the method. The idea of 3D imaging was thus abandoned and the need for PA cephalograms in the orthodontic practice sharply diminished.

Advancements in orthodontics such as techniques for palatal widening, maxillary orthopedics, increased awareness of the relationship between respiration and growth, and

increased ability to treat dental and skeletal asymmetries, revived the need for a valid assessment tool.³ The PA cephalogram was the only radiographic view that could show the width and angulation of the maxillary and mandibular dental arches, their relation to the respective dento-alveolar bases, the skeletal bases of the maxilla and mandible in transverse and vertical plane of space, and their relationship to the rest of the cranial bones. In addition, it revealed the size of the nasal cavity and deviations of the nasal septum. The relative vertical dimensions of bilateral osseous structures could also be assessed.³⁻⁸

At present, orthodontists request PA cephalograms when there is a need to evaluate obvious dento-facial and skeletal asymmetries and relate dental midline discrepancies to skeletal asymmetries. Evaluation of posterior cross-bites, maxillary anatomy, suspected nasal obstruction or presence of signs and symptoms of TMJ dysfunction are other most common reasons for ordering PA cephalograms.^{9, 10} If patient positioning in the cephalostat is adequate the posterior-anterior (PA) cephalogram should accommodate the right and left sides at a relatively equal distance from the film and source, which should allow orthodontists to locate and measure asymmetries in vertical and transverse proportions.

As with other conventional radiographic techniques, PA cephalometry involves a series of technical and analytical problems. The first group of problems relates to magnification and distortion, which inevitably occur due to the geometry of the radiographic set-up and the conversion of a 3D object onto a 2D film. Variations in enlargement between anatomical structures located at various A-P distances from the frontal film have been

reported to range between 0.3% and 9.2 %.¹¹ Distortion is closely associated with magnification but is a distinct problem in cephalometry. It results from intricate magnification combinations for each part of the imaged structure not only relative to A-P but also radial distance (radial displacement) ¹² Variations in head positioning as well as patient movement in the cephalostat during exposure further contribute to distortion. Studies that have evaluated error due to patient positioning and head rotation have in general agreed that if due care is taken when placing the patient in the cephalostat the error is negligible. ¹³⁻¹⁶ Landmark identification errors in PA cephalometry have also been reported. ^{17,18} Each landmark has been found to demonstrate a characteristic envelope of error in the vertical and transverse plane of space. Dental landmarks have been reported to be less reliable than skeletal, ranging in error between 0.37 to 1.10mm. ¹⁷ If more than one observer is involved in PA landmark location the error significantly increases (0.31mm to 4.79 mm). ¹⁸ Many landmarks used in PA cephalometric analyses have an unacceptable magnitude of error. ¹⁸

The purpose of this study was to evaluate the validity of commonly used PA cephalometric landmarks in representing changes in position of the dento-facial complex. The relationship between various experimentally created dento-facial manipulations and the same represented on PA cephalograms were studied. A specific goal was to evaluate whether the changes in the anterior-posterior dimension were significantly related with the ability of PA cephalometric landmarks in evaluating the position of dento-facial structures.

2.2 MATERIALS AND METHODS

2.2.1 Experimental Design

An experimental three-dimensional model was created using a human dry skull with no visible damage to the maxilla and mandible, and with intact dentition including second molars. Twenty-nine landmarks were located on the surface of the skull by using precise definitions available from the literature (Table 2.1). Of these, 5 were located in the upper cranium, 10 in the maxilla and 14 in the mandible (Figure 2.1) Using a dental slow-speed hand piece and a round carbide bur (size2) shallow semi-spherical concavities were drilled in the skull to mark the location of all landmarks. Chromium-steel markers of 1/16" (1.5875 mm) diameter were fitted tightly into the concavities and glued in place.

The two jaws were occluded following the patterns of attrition and cusp-fossa morphology on the occlusal surfaces. The mandible was securely attached to the maxilla using wire inter-maxillary fixation. This maxillo-mandibular unit was then "freed" from the skull by making a cut above the maxillary body as in Le Fort I osteotomy. Both jugal points (JP-R, JP-L) remained a part of the movable maxillo-mandibular complex (Figure 2.1).

2.2.2 Method of creating experimental manipulations of the dento-facial complex

In order to create various known dento-facial positional changes a custom-made moving apparatus (MA) was designed (Figure 2.2). It consisted of the following three main units:

- a. A metal platform (156 mm x 200mm) that served as a base onto which the other components were mounted.
- b. A skull holder, represented by a cylinder-shaped lucite rod that was attached to the area of foramen magnum at the upper end, and to the platform at the lower end. The skull holder was designed in such a way so as to maintain the skull with its Frankfort horizontal parallel to the base. For this purpose the vertical positions of points orbitale inferior right and left (OI R/L) and porion right and left (Po R/L) were levelled and verified with a Coordinate Measuring Machine (described further in this section). In addition, point Nasion (Na) was aligned with the middle of the metal platform.
- c. A system of moving parts designed to provide three types of movement:
 - ◆ translation
 - ◆ vertical rotation (rotation around a vertical axis)
 - ◆ horizontal rotation (rotation around a horizontal axis)

The moving parts consisted of another lucite rod attached to the inferior border of the mandible at the upper end, and inserted into a well-fitting bearing at the lower end. The fit at the lower end was such that the lucite rod could be manually rotated. The bearing was embedded into a smaller metal piece that also served as an attachment to a microscope platform with a control dial for transverse movement. Thus, the lucite rod

with the maxillo-mandibular complex attached at its upper end could move sideways along the microscope platform, and could also rotate around its long axis. The third type of movement was provided by an indirect attachment between the mandible and the upper end of the rod. It consisted of a small lucite plate glued onto the mandible and screwed into the anterior part of the rod with a plastic screw placed horizontally in an anterior-posterior direction. This piece allowed for the maxillo-mandibular complex to be rotated around a horizontal axis represented by the long axis of the screw.

All movements were measured from what was termed the initial or “neutral” position (NP) (Fig. 2.3). Recognizing the fact that a normal degree of asymmetry existed in the skull, an attempt was made to “center” the skull by aligning all midpoints. The transverse coordinates of points nasion (Na), anterior nasal spine (ANS), Incisal Superior (InS), Incisal Inferior (InI), and point Menton (Me) were measured using the Coordinate Measuring Machine (CMM). The CMM verified that the transverse position of N, ANS, InS and InI were identical, however, Me could not be aligned with the rest of the midpoints without having to rotate the maxillo-mandibular complex and significantly changing the position of both jaws. Therefore it was decided not to include Menton in the alignment process.

To create translational manipulations, the control dial was turned to slide the jaws along the millimetric scale of the microscope platform (Fig. 2.4 a). A total of 10 movements were produced. These consisted of 5 movements towards the skull’s right side (right translation or RT) at 1.5-mm increments (1.5mm, 3mm, 4.5mm, 6mm and 7.5mm) and 5 movements towards the left side (LT) at the same increments.

For rotation around vertical axis (termed vertical rotation) the lucite rod was rotated around its long axis away from the neutral position (NP), towards the right side and left side, respectively. Figure 2.4 b shows the axis of vertical rotation that passed vertically through the centre of the lucite rod mounted under the mandible. These movements were measured using a protractor that was glued on the rod and set at 90 degrees in the neutral position. A metal pointer marked the neutral position or the centre from which all subsequent vertical offsets were measured on the protractor. Right side rotation (RVR) was defined when the maxillo-mandibular unit was being rotated towards the skull's right side, and the opposite rotation represented left vertical rotation (LVR). On each side, five degrees of movement were recorded at 1.5, 3, 4.5, 6 and 7.5 degrees for a total of 10 rotations.

Rotation around a horizontal axis (horizontal rotation) was achieved by rotating the maxillo-mandibular complex around the horizontal axis that passed in an anterior-posterior direction, through the length of the plastic screw that attached the maxillo-mandibular complex to the anterior lucite rod (Fig. 2.4 c). Rotations were made first towards the right side, then towards the left side, at 1.5, 3, 4.5, 6 and 7.5-degrees (total of 10). Right horizontal rotation (RHR) was defined when point Me shifted toward the right side of the skull. The increments of movement were measured by the vertical protractor that was glued onto the small lucite plate immediately below the mandible. The neutral position was marked with a line scribed onto the lucite rod, and each rotational movement was measured as an offset from this line.

2.2.3 Method of measuring positional changes of landmarks in 3-D Space

The position of all maxillary and mandibular markers in the neutral position as well as all created positions (total of 31) was measured with the use of a Coordinate Measuring Machine (CMM), (Starrett^R Premis No. HGC Series Manual, Mount Airy, North Carolina, USA). The machine features a granite plate as a base and a movable, hollow, granite-ceramic bridge that carries the arm with the measuring probe. The carriage of the arm can slide from side to side along the entire length of the bridge, while the bridge can slide front-to-back over the granite base. The arm can be adjusted vertically in up-down direction until the proper height for measurement is achieved. The unique combination of granite and ceramic offers reduced weight and excellent stability during the measuring process, which is further enhanced by the smooth movement of all parts provided by preloaded air bearings in all three axes (x, y and z). Another unique feature of the machine is the ability to change the angulation and/or rotate the measuring probe. This change of orientation of the probe improves access to the point to be measured. Thus, the CMM has the capability of measuring the position of any given point within its measuring range and provides a reading that consists of x-coordinate (transverse axis), y-coordinate (anterior-posterior axis) and z-coordinate (vertical axis).

A focal point of the CMM operation is the CMM software, the Starett Measure Manager (SMM). It is a flexible, easy to use program that runs in a graphical window environment under the OS/2 multi-tasking operating system. The very first task after start-up of the machine is to place the CMM probe in the home position. This is done by: a). pulling the bridge all the way forward, b). moving the arm to the top most position, and c). moving

the carriage of the arm to the far left. Homing is important because a fixed zero position is used by the error mapping system to achieve the highest accuracy. After homing the probe, the SMM mode selection screen is displayed. The SMM has four modes of operation. For the purposes of this study, the “Learn” mode was used, which saved each step performed by the operator in a customized measurement program. Test probing revealed that the orientation of the measuring probe would have to be changed to be able to approach each chromium marker from a direction of greatest convenience. Therefore, three other reference probes were created and saved as new probes in the SMM program. The next crucial point before each measuring cycle was to transfer the CMM coordinate system origin onto the skull/moving device. This eliminated the need to physically align the skull with the CMM coordinate system. A “skull coordinate system” (SCS) was created by using the “datum creation feature” from the SMM menu. The metal platform of the moving apparatus was used as a stable surface for establishing the origin and aligning the SCS. The frontal surface of the moving apparatus’ metal platform was used as the primary plane for axis alignment. The upper edge of the frontal surface of the platform was used to define the x-axis, while the origin of the SCS was established at the left corner-point of the upper edge on the frontal surface of the platform. The arrow in Figure 2.3 points to the origin of the skull coordinate system.

All markers were located by touching each one individually with the tip of the measuring probe ($d=1\text{mm}$). The results for each data point were displayed on the screen and printed as x, y, and z coordinates. This sequence of measurement was performed for the neutral position and was saved as a measuring protocol that was afterwards re-used through the “Run” mode of the SMM. The run mode simply replayed the steps in the program and

provided consistency for repeated measurements as well as reduced possibility for errors. Using the moving apparatus the maxillo-mandibular unit was guided into all previously defined asymmetries, and the location of the markers at each increment of movement was measured in 3-D space. All measurements were repeated three times in order to minimize random error.

2.2.4 Posterior-anterior Cephalometric Technique and Digitization Procedure

The skull with the moving apparatus was placed on a stable flat surface and carefully positioned in the cephalostat of a Siemens cephalometric machine (Siemens Electric Ltd. Bensheim, Germany) for posterior-anterior exposure. The film-source distance was fixed at 130". Several test films were taken to establish the setting that provided radiographs of the best quality (75kV, 6mA and 0.4 sec).

The maxillo-mandibular unit was moved into all previously described types of movement and a PA cephalogram was taken after each change. This amounted to a total of thirty-one PA exposures. Prior to developing the film, each movement was given a 4-digit number code and this number was stamped on the corresponding radiograph.

All PA cephalograms were scanned using a Umax Astra 1200S Scanner at 1200dpi and reduced to 20% of the original size. The images were saved as bitmap files and stored onto a CD-Rom. A custom-made digitization protocol was developed to locate all markers in a defined coordinate system (Ceph Caliper Ltd). After opening each image file, points Orbita Superior R and Orbita Superior L were located. The program used

these two points to draw a line between them and to establish a point at a fixed distance to the left from the OS L along the line. From this point, another line perpendicular to the OS line was dropped vertically and the origin of the coordinate system was set at the same fixed distance along this line. This method allowed for the coordinate system to be aligned with the OS line, and to have an origin in the lower left corner of the radiograph, which produced positive coordinates for all landmarks. Once the origin was established, each landmark was located by clicking with the mouse locator on the computer screen. Each radiograph was digitized three times on separate occasions.

2.2.5 Method Error

The total error of measurement in the study could result from the following contributing factors:

1. Accuracy of the CMM
2. Error due to intra-observer variability when locating landmarks with CMM
3. Error due to moving apparatus (MA)
4. Error due to intra-observer variability when locating landmarks with computer-aided digitization

The linear accuracy of the CMM is 0.0038 mm per axis as reported by the manufacturer.

¹⁹ It is thoroughly inspected and calibrated at the time of instalment with equipment that is traceable to the US National Institute of Standards and Technology.

The intra-observer reproducibility in locating the spherical markers with the CMM was

tested by repeated measurement of six point-to-point distances between randomly selected landmarks on five occasions in the neutral head position. Two distances were measured on the upper cranium (N-ZFL, OSR-OIR), two on the maxilla (JL-ANS, InS-Mx6L) and two on the mandible (CoSL-InI, AgL-AgR).

The repeatability of the moving apparatus was tested in a pilot study. Five different movements incorporating all three types of manipulations were created with the apparatus. The x, y and z coordinates of five randomly chosen landmarks (ANS, JR, Mx6 R, InI and Me) at each movement were recorded with the CMM. The same protocol was used on five occasions. The error of repeated measurement between two occasions was calculated for each landmark as a composite score of the distance between the three co-ordinate measures based on the following formula:

Distance between first and second measurement= square root $((x1-x2)^2 + (y1-y2)^2 + (z1-z2)^2)$

(where x1,y1,z1 were the co-ordinates obtained in the first occasion, x2,y2,z2 the co-ordinates from the second occasion)

The same formula was used to calculate the distances between the first and third, the first and fourth, and first and fifth measurement. These four distances were used to calculate a mean, maximum, minimum and standard deviation of repeated error for each landmark at each of the five movements.

Additional control over random error was achieved by repeating all measurements with

the CMM three times. In this way, for every movement of the maxillo-mandibular complex created with the apparatus, there were three repeated values for each coordinate (x1, y1, z1, x2, y2, z2 and x3, y3, z3) for each landmark. The differences between these three repeated measures were calculated for each landmark separately using the same formula previously described. Three differences of measurement were produced between the first and the second, the second and third and the first and third repeated measure.

Investigator bias during the digitization process was minimized since all cephalograms were coded with random numbers and the investigator had no knowledge of the type of movement the cephalogram represented. Landmark identification error in this study was reduced by the use of spherical chromium-lead markers. The centre of the radiographic image of the markers was the digitizing target. All radiographs were digitized on three separate occasions. The error of repeated measurement between two digitizing occasions of the same radiograph was calculated for each landmark as a composite score of the distance between the x and y co-ordinate measures based on the following formula:

Distance between first and second digitization = square root $((x1-x2)^2+(y1-y2)^2)$

(where x1,y1 were the co-ordinates obtained in the first digitization, x2,y2 the co-ordinates from the second digitization)

The same formula was used to calculate the differences between the second and third, and the first and third digitization. A total of 31 means and 31 standard deviations were produced of the three distances for each landmark on the individual PA cephalograms. The total error of repeated digitization of each landmark was calculated across all PA cephalograms as mean and standard deviation of the 31 individual means. In addition, a

mean of the 31 standard deviations was produced.

Another source of measurement error could have been the diameter of the markers used (1.58 mm). In the 3D measurements the markers were located by touching them on the surface, while in the 2D measurements they were located by the center of the radiographic outline. Theoretically the difference of measurement between the 3D and the 2D landmarks' locations could have been at least 0.79 mm (the radius of the metal marker). However, this type of measurement error was not crucial since the data were compared not by the actual co-ordinates of landmarks in 3D and 2D but by increments of positional change. For as long as the intra-observer repeatability when locating the landmarks with the CMM and on the PA cephalograms was adequate this source of error should not have been an issue.

2.2.6 Statistical Analyses

In the 2D files the code number of each radiograph was replaced with an abbreviation for the type and amount of movement that each represented. The order of data in the 2D files was matched with that in the 3D data for both x and y coordinates. For each landmark average values of the three-times repeated measures for each coordinate were calculated in both the 3D and 2D data.

The increment of change in the location of each landmark when the jaws were moved was calculated for both the 2D and 3D data. The values of the x and y coordinate in the neutral position were subtracted from the x and y coordinate for all created asymmetric

movements. For each landmark the following increments were produced:

$X(\text{movement}) - X(\text{neutral})$

$Y(\text{movement}) - Y(\text{neutral})$

In this way for each landmark a total of 30 values were produced for the x-axis (transverse increments of change) and 30 values for the y-axis (vertical increments of change). These values were used in two regression analyses that tested the relationship between the true asymmetry in 3D and the radiographic asymmetry in 2D for the transverse and vertical axis separately.

The potential relationship between landmarks' validity for transverse measurements and the changes in the z-axis (third dimension) was also tested with regression analyses. Vertical rotations of the 20 peripheral landmarks were used for this purpose since sufficient anterior-posterior changes were introduced during these manipulations. The increments of change in the z-coordinate of each landmark during vertical rotations, as measured with the CMM, were calculated between the neutral position and the 30 manipulations. These values were used as the dependent variable. For each landmark the differences between the 3D and the corresponding 2D data were calculated for the x axis for all vertical rotations. These values were used as the independent variables.

2.3 RESULTS

Intra-observer reproducibility of measurement with the CMM was adequate (Table 2.2). The range of standard deviations of repeated measurements was between 0.09 and 0.58 mm.

The MA reproducibility error ranged between 0.33 ± 0.06 to 0.87 ± 0.39 mm (Table 2.3). The reproducibility of the moving apparatus was therefore acceptable since the error was smaller than the smallest increment of change created with the apparatus (1.5 mm).

Error due to locating landmarks with CMM was also small. The range of error was between 0.14 ± 0.05 mm for right Nasal Cavity Inferior to 0.63 ± 0.3 mm for right Maxillary Molar (Table 2.4).

The mean error of landmark identification ranged from 0.33 ± 0.17 mm for right Condyle Centre to 0.60 ± 0.29 mm for right Maxillary Cuspid (Table 2.5). Two landmarks showed random error larger than 1 mm (Mx3R, Me). The largest error occurred when Maxillary Right Cuspid was located (1.18mm).

The results of the regression analyses between the 3D and 2D data for the x and y axes are presented in Table 2.6. The nature of the association between the 3D and 2D data is expressed by the three indicators included in Table 2.6 (R^2 , constant and slope). All three factors need to be considered in the order they are presented in the table. The adjusted R^2 values are an overall measure of the linear relationship, or the goodness-of-fit, between

the 3D and 2D data. When multiplied by 100 they express the percentage of the variability in the 3D data that is explained by the 2D data. The constant and the slope are the parameters that describe the linear relationship between the tested variables. For an ideal fit of the regression line, the constant should be zero, and the slope should be one. As seen in Table 2.6, all adjusted R^2 values for the x-axis were high, ranging between 0.888 (89%) for Menton to 0.989 (99%) for Incisor Superior. Landmarks ANS, CoSL, JPR, Mx3R, Mx6L, and NCIR also had constants very close to zero, and therefore represented transverse changes most accurately. The slopes for all regressions were close to one. The adjusted R^2 values for the vertical dimension (y-axis) were moderate to high for all peripheral landmarks. The four midline landmarks, including Anterior Nasal Spine, Incisor Superior, Incisor Inferior and Menton could explain less than 70% of the 3D values. Menton and Incisor Inferior point had the smallest adjusted R^2 value at 0.394 (39.4%) and 0.405 (40.5 %) respectively. The highest adjusted R^2 value was found for the left Condyle Centre at 0.943 or 94.3%. From those landmarks that showed more than 70% of association with the 3D data only two landmarks had constants close to zero (Md3L and NCIL), and six landmarks had slope values that were less than 0.9 (AgL, AgR, GoL, GoR, Md3L, Md3R).

The results of the regression analyses between the 3D and 2D data for the x and y- axes are presented in Table 2.6. The three indicators included in Table 2.6, adjusted R^2 , constant, and slope, express the association between the 3D and 2D data. All three factors need to be considered in the order they are presented in the table. The adjusted R^2 values are an overall measure of the linear relationship, or the goodness-of-fit, between the 3D and 2D data. When multiplied by 100 they express the percentage of the

variability in the 3D data that is explained by the 2D data. The constant and the slope are the parameters that describe the linear relationship between the tested variables. For an ideal fit of the regression line, the constant should be zero, and the slope should be one. As seen in Table 2.7, all adjusted R^2 values for the x-axis were high, ranging between 0.888 (89%) for Menton to 0.989 (99%) for Incisor Superior. Landmarks ANS, CoSL, JPR, Mx3R, Mx6L, and NCIR also had constants very close to zero, and therefore represented transverse changes most accurately. The slopes for all regressions were close to one. The adjusted R^2 values for the vertical dimension (y-axis) were moderate to high for all peripheral landmarks. The four midline landmarks, including Anterior Nasal Spine, Incisor Superior, Incisor Inferior and Menton could explain less than 70% of the 3D values. Menton and Incisor Inferior point had the smallest adjusted R^2 value at 0.394 (39.4%) and 0.405 (40.5 %) respectively. The highest adjusted R^2 value was found for the left Condyle Centre at 0.943 or 94.3%. From those landmarks that showed more than 70% of association with the 3D data only two landmarks had constants close to zero (Md3L and NCIL), and six landmarks had slope values that were less than 0.9 (AgL, AgR, GoL, GoR, Md3L, Md3R).

A summary of significant findings from the regression analyses between the changes of the z-coordinate during vertical rotations and the differences between 3D and 2D data along the x axis is presented in Table 2.7. In total, only one landmark (Mx3 L) showed significant relationship between the transverse 3D-2D differences of measurement and its changes in the third dimension. The adjusted R^2 value is an overall measure of goodness-of-fit between the landmark's re-positioning in the third dimension and the differences between the landmarks' 3D and 2D increments of change in the horizontal axis. The p-

value of the slope, i.e. the regression coefficients for the x – axis was smaller than 0.05 the slopes and indicated significant correlation with the third dimension.

2.4 DISCUSSION

The focus of this study was to evaluate the validity of commonly used PA cephalometric landmarks for representing the actual position of dento-facial structures. PA cephalometric landmarks are used to measure transverse and vertical dimensions of dento-facial structures and to assess dento-facial asymmetries. The entire analysis relies upon the ability of the used landmarks to convey accurate information about the structures they represent.

Every attempt was made in this study to control the factors that could contribute to errors in the PA radiographic process and analysis of the radiographs. Since previous studies have reported that the largest error in cephalometry is due to landmark identification^{20, 21} chromium-steel markers were used to facilitate the process of locating landmarks. In practice landmark identification with an error below 1 mm is considered a precise measurement.²² Landmark identification error in this study was below 1 mm for 22 landmarks out of 24 used, and as such was smaller than previously published error without markers^{17,18} and with metal markers.²³ The reported landmark identification error in this study included error along both axes, and could have been significantly larger than in previously published studies that have reported the error along the x and y axis separately. As noted previously, this was not the case.

Regression analyses were used to explore the relationship between the movement of each landmark through the full range of asymmetric manipulations, and the same changes for

each landmark measured from PA cephalograms. The results pointed out that all 24 PA landmarks were able to show at least 90% of the horizontal changes in truth. Menton was the only exception and could reveal 88% of the transverse changes. The findings along the vertical axis showed a great deal of variability. Ten PA landmarks were able to represent at least 90 % of the changes completed by their 3D counterparts (adj. R^2 values >0.90). The adjusted R^2 values for the four midline landmarks including Anterior Nasal Spine, Incisor Superior, Incisor Inferior and Menton seemed to indicate that these landmarks represented the 3D changes to a limited degree ($0.394 < R^2 < 0.628$). The adjusted R^2 was the lowest for Menton, followed by Incisor Inferior, Incisor Superior, and Anterior Nasal Spine, in increasing order. However, these findings are of limited value due to the nature of the created manipulations. In translation and vertical rotation the vertical shift of all landmarks, midline and peripheral included, would have been minimal. During horizontal rotations the vertical shift of the midline landmarks would have been smaller than the shift of peripheral landmarks, since the point of rotation was located below the midline of the skull and underneath Menton. The farther horizontally the landmarks were from the point of rotation, the greater their vertical movement would have been during horizontal rotation. Menton was the closest point to the axis of rotation and shifted the least compared to the other midline and peripheral landmarks. Incisor inferior, Incisor Superior and Anterior Nasal Spine were the other landmarks that were located along the midline and at increasing distances from the point of horizontal rotation. The actual plots on midline landmarks vertical increments of change are presented in Appendix 1. The plots showed that the ranges of vertical changes in the 3D and 2D data were in fact smaller than the error of measurement. Therefore, the validity

of midline landmarks for vertical measurements cannot be determined based on these values.

Only one landmark (Mx3 L) out of 20 that were tested showed significant relationship between the changes in the anterior-posterior direction and its ability to represent the transverse changes during the 10 vertical rotations. This finding points out that the lack of a third dimension is not significantly related to the ability of most peripheral landmarks to show the transverse changes of the dento-facial structures. This result however may have been due to the particular degrees and manipulations introduced in the experiment.

This study cannot be directly compared to previously published research. Partial comparison could be made with a study by Pirttiniemi et al.²³ In an experiment designed to calculate the horizontal geometric error due to head rotations around the vertical axis they found that the smallest geometric “error” i.e. the lowest deviation from the midline was recorded for landmarks near the mid-sagittal plane (InS, InI, Me) and the largest “error” was recorded for the most lateral points (Condylar points, Antegonion). By extrapolation it could be expected to find that those landmarks located in the midline would show the least association with displacement asymmetries, while those on the periphery would be most capable of showing displacement asymmetries. However, the findings in the present study, as seen from Table 2.6, showed that all landmarks, midline and peripheral included, represented the changes in the horizontal direction with almost equal precision. The lowest association was found for Menton (88%). It should be remembered that the displacement asymmetries created in this study included not only rotations around the vertical axis but also translations and horizontal rotations.

The experimental model was used to create positional changes of the maxillo-mandibular complex of known type (translation, vertical and horizontal rotation), amount (increments of 1.5 to 7.5 mm or degrees) and direction (right or left). The created deviations represented asymmetric positions of the dento-facial complex that ranged from mild to severe. The objective was to keep them within a range that could be found both in patients with normal asymmetry and in patients with more obvious cranio-facial deformities. A suggested future research could focus on milder range of asymmetries and smaller increments of asymmetric changes. The same methodology as the one used in this study could be used to establish the validity of landmarks in distinguishing between more discrete asymmetries ranging from mild to moderate. Also, in order to determine the validity of midline landmarks for vertical measurements a larger range of vertical changes should be created.

This study was a carefully rendered experiment. Therefore, the results cannot be directly applicable to a clinical situation in which the PA films are not taken under the same conditions to those created in this experiment. Also, landmarks in this study were located with the use of chromium-steel markers. In clinical practice landmark identification error is by far the largest source of error in cephalometric analysis.^{20,21} It should be emphasized that landmark validity and reproducibility are not identical but complementary sources of error. For this reason the results from this study should serve as a guideline for choosing landmarks that are valid, keeping in mind that additional error due to landmark identification will further decrease the usefulness of certain landmarks for PA analysis of the dento-facial structures. In addition, studies have shown that

landmark identification error on PA films of real patients is larger than on films of dry skulls.¹⁸ Another source of error is inaccurate head positioning in the cephalostat. Rotations of the patient in the cephalostat around the horizontal (trans-meatal) or vertical axis up to 5 degrees have been reported to have no significant effect on the magnitude of landmarks' identification error.^{13, 14} More significant rotations may affect the validity of PA cephalograms and produce clinically unacceptable measurements.

2.5 CONCLUSIONS

1. The 24 PA cephalometric landmarks could accurately represent positional deviations of maxillary and mandibular structures in the horizontal (transverse) dimension. All 24 PA landmarks can be used to measure changes in the transverse dimension, provided landmark identification error is minimal.
2. Changes in the vertical dimension can be represented by PA landmarks with variable accuracy, depending on landmark location. The correlation coefficients between changes in 3D and 2D in the vertical axis were the lowest for Antegonion Right (73.6 %) 60.6% to 94 % for Condyle Centre Left.
3. The validity of landmarks to represent changes in the vertical dimension has a tendency to decrease from peripheral landmarks to landmarks located closer to the midline.
4. The ability of all peripheral landmarks, with exception of Maxillary Cuspid Left, to represent changes in the transverse direction was not significantly related to the changes that were created in the anterior-posterior direction during vertical rotations in this experiment. However, this result may have been due to the types of movements introduced in the experiment.

Table 2.1. List of Landmarks and their Definitions

Cranial Landmarks

Na	Nasion- the point of contact between the frontal bone and the suture between the two halves of the nasal bones
OS R/L	Orbitale Superior- the midpoint of the superior orbital margin, right and left
OI R/L	Orbitale Inferior- the midpoint of the inferior orbital margin, right and left
Po R/L	Porion- the uppermost point of the external auditory meatus, right and left

Maxillary landmarks

ANS	Anterior nasal spine- the centre of the intersection of the nasal septum and the palate
InS	Incisor point Superior- the crest of the alveolus between the upper incisors
NCI R/L	Nasal Cavity Inferior- the lowermost point on the inferior curvature of the nasal cavity
JP R/L	Jugal Point- the deepest point on the curve of the malar process of the maxilla
Mx6 R/L	Maxillary first molar- the midpoint of the buccal surface of the maxillary first molar
Mx3 R/L	Maxillary cuspid- the tip of the maxillary cuspid right and left

Mandibular landmarks

InI	Incisor point Inferior- the crest of the alveolus between the lower incisors
Me	Menton- the midpoint on the inferior border of the mental protuberance
CoS R/L	Condyle Superior- the most superior aspect of the mandibular condyle
CoC R/L	Condyle Center- the center of the mandibular condyle
Ag R/L	Antegonion- the deepest point on the curvature of the antegonial notch

- Go R/L Gonion-the midpoint on the curvature at the angle of the mandible
right and left
- Md6 R/L Mandibular first molar- the midpoint of the buccal surface of the
mandibular first molar right and left
- Md3 R/L Mandibular cuspid- the tip of the mandibular cuspid right and left

Table 2.2. Intra-observer Reproducibility in Measuring Landmark Position with Coordinate Measuring Machine (CMM): Five Times Repeated Measures of Five Randomly Selected Distances (in mm)

<u>Occasion</u>	<u>N-ZFL</u>	<u>OSR-OIR</u>	<u>JL-ANS</u>	<u>InS-Mx6L</u>	<u>CoSL-InI</u>	<u>AgL-AgR</u>
1	49.83	33.65	44.21	20.22	106.60	67.27
2	49.73	33.76	44.26	20.52	106.98	67.06
3	49.78	33.85	44.32	20.41	107.08	66.99
4	49.70	32.52	44.09	19.93	106.60	67.25
5	49.93	33.94	43.68	20.03	106.99	67.25
Mean	49.79	33.55	44.11	20.22	106.85	67.16
SD	0.09	0.58	0.25	0.25	0.23	0.13

Table 2.3. Reproducibility of Moving Apparatus (MA): Error of measurement due to five times repeated measures of five selected points. Means, standard deviations, maximum and minimum values of differences between the first and subsequent four repeated measures (in mm).

<u>Statistics</u>	<u>ANS</u>	<u>JPR</u>	<u>Mx6L</u>	<u>InI</u>	<u>Me</u>
Mean	0.87	0.46	0.47	0.77	0.71
SD	0.07	0.24	0.08	0.20	0.26
Max	0.95	0.81	0.56	0.92	1.03
Min	0.77	0.27	0.39	0.49	0.49
Mean	0.63	0.53	0.55	0.87	0.62
SD	0.31	0.20	0.17	0.39	0.22
Max	0.91	0.69	0.70	1.26	0.84
Min	0.20	0.24	0.32	0.33	0.31
Mean	0.73	0.81	0.33	0.85	0.78
SD	0.21	0.13	0.06	0.20	0.08
Max	0.95	0.99	0.40	1.07	0.88
Min	0.53	0.70	0.27	0.63	0.68
Mean	0.62	0.78	0.36	0.46	0.44
SD	0.11	0.20	0.22	0.15	0.28
Max	0.77	0.95	0.66	0.68	0.85
Min	0.50	0.50	0.18	0.36	0.21
Mean	0.85	0.50	0.70	0.47	0.52
SD	0.18	0.24	0.20	0.20	0.15
Max	1.00	0.83	0.81	0.78	0.65
Min	0.63	0.31	0.40	0.35	0.30

Table 2.4. Intra-observer Error of Repeated Measurement of Landmarks' Locations with Coordinate Measuring Machine (CMM) (in mm).

<u>Landmark</u>	<u>Mean Error</u>	<u>SD of</u> <u>mean error</u>	<u>Mean of SD</u>
AgL	0.24	0.09	0.11
AgR	0.21	0.11	0.09
ANS	0.23	0.15	0.11
CoCL	0.15	0.05	0.05
CoCR	0.20	0.07	0.07
CoSL	0.16	0.07	0.07
CoSR	0.18	0.07	0.08
GoL	0.25	0.13	0.13
GoR	0.23	0.20	0.13
InI	0.20	0.08	0.08
InS	0.16	0.07	0.07
JPL	0.25	0.14	0.13
JPR	0.21	0.10	0.10
Md3L	0.35	0.23	0.16
Md3R	0.39	0.19	0.18
Md6L	0.16	0.06	0.07
Md6R	0.22	0.13	0.11
Me	0.40	0.20	0.18
MX3L	0.63	0.14	0.30
Mx3R	0.31	0.10	0.15
Mx6L	0.21	0.10	0.10
Mx6R	0.22	0.10	0.10
NCIL	0.16	0.07	0.07
NCIR	0.14	0.06	0.05

Table 2.5. Intra-observer Error of Computer-aided Location of Cephalometric Landmarks.

<u>Landmark</u>	<u>Mean</u>	<u>SD of mean</u>	<u>Mean of SD</u>
	<u>Error</u>	<u>error</u>	
AgL	0.50	0.21	0.23
AgR	0.49	0.25	0.22
ANS	0.33	0.14	0.13
CoCL	0.35	0.15	0.17
CoCL	0.34	0.14	0.14
CoCR	0.33	0.14	0.17
CoSR	0.35	0.14	0.15
GoL	0.50	0.21	0.24
GoR	0.47	0.20	0.21
InI	0.42	0.21	0.21
InS	0.37	0.13	0.16
JPL	0.36	0.18	0.18
JPR	0.40	0.27	0.19
Md3L	0.39	0.13	0.20
Md3R	0.43	0.19	0.25
Md6L	0.43	0.19	0.21
Md6R	0.44	0.17	0.20
Me	0.55	0.24	0.25
Mx3L	0.52	0.26	0.24
Mx3R	0.60	0.32	0.29
Mx6L	0.44	0.19	0.20
Mx6R	0.43	0.19	0.19
NCIL	0.36	0.17	0.19
NCIR	0.34	0.13	0.16

Table 2.6. Relationship between Increments of Change Measured in Truth (3D space) and PA Cephalograms (2D space)

<u>Landmark</u>	<u>X-axis</u>			<u>Y- axis</u>		
	<u>Adj.R²</u>	<u>Constant</u>	<u>Slope</u>	<u>Adj. R²</u>	<u>Constant</u>	<u>Slope</u>
AgL	0.96	-0.584	0.932	0.777	0.394	0.822
AgR	0.955	-0.525	0.935	0.736	-0.296	0.806
ANS	0.985	-0.008	0.98	N/A	N/A	N/A
CoCL	0.974	0.229	1.005	0.943	0.103	0.982
CoCR	0.974	0.153	1.013	0.924	-0.409	0.97
CoSL	0.972	0.007	1.008	0.94	0.274	0.981
CoSR	0.973	0.253	1.018	0.93	-0.34	0.976
GoL	0.968	-0.461	0.951	0.768	0.396	0.835
GoR	0.967	-0.452	0.947	0.761	-0.19	0.824
INI	0.988	-0.341	0.978	N/A	N/A	N/A
INS	0.989	-0.241	0.978	N/A	N/A	N/A
JPL	0.979	0.214	0.972	0.942	0.25	0.934
JPR	0.978	-0.006	1.017	0.905	-0.175	0.931
Md3L	0.933	0.233	0.99	0.86	-0.005	0.851
Md3R	0.919	-0.16	0.942	0.808	-0.13	0.819
Md6L	0.987	-0.171	0.98	0.931	0.174	0.916
Md6R	0.985	-0.314	0.971	0.913	-0.35	0.911
Me	0.888	-0.364	0.867	N/A	N/A	N/A
Mx3L	0.987	0.589	0.991	0.888	0.232	0.908
Mx3R	0.931	0.007	0.972	0.874	0.243	0.999
Mx6L	0.986	-0.007	0.985	0.932	0.23	0.902
Mx6R	0.986	-0.221	0.975	0.921	-0.185	0.93
NCIL	0.983	-0.147	0.985	0.847	0.006	0.932
NCIR	0.983	-0.006	0.975	0.88	-0.168	1.023

Table 2.7. Relationship between Transverse Changes Represented on PA films and the Third dimension (z-coordinate). Summary of Significant Results of the Regression Analyses Using the Differences between 3D and 2D data in the Transverse axis during Vertical Rotations as Independent Variables and z-coordinate as Dependent Variable.

Vertical Rotation	Adjusted R²	p-value of the Regression Coefficient
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Mx3L	0.46 (46%)	.019*
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- significance at 5% level

References

1. Broadbent BH. A new x-ray technique and its application to orthodontia. *Angle Orthod* 1931;1:45-66.
2. Baumrind S, Moffitt FH, Curry S. Three-dimensional x-ray stereometry from coplanar images: A progress report. *Am J Orthod* 1983;84(4):292-312.
3. Ricketts RM. Perspectives in the clinical application of cephalometrics: the first fifty years. *Angle Orthod* 1981;51:115-50.
4. Bergman R. Practical application of the PA cephalometric headfilm. *Orthod Rev* 1988;March/April:20-26.
5. Sassouni V. Diagnosis and treatment planning via roentgenographic cephalometry. *Am J Orthod* 1958;44:433-463.
6. Ricketts RM, Roth RH, Chaconas SJ, Schulhof RJ, Engel GA. *Orthodontic Diagnosis and Planning*. Denver: Rocky Mountain Data Systems, 1982.
7. Grummons DC, Kappeyne van de Coppelo MA. A Frontal Asymmetry Analysis. *JCO* 1987;21:448-65.
8. Vogel CJ. Correction of frontal dimensions from head x-rays. *Angle Orthod* 1967;37:1-8.
9. Luke SL, Lee P, Atchison KA, White SC. Orthodontic residents' indications for use of the lateral TMJ Tomogram and the Posterioanterior Cephalogram. *J Dent Educ* 1997; 61:29-36.
10. Tyndall DA, Turner SP. Radiographic materials, methods and film-ordering patterns among orthodontic educators and private practitioners. *Am J Orthod Dentofac Orthop* 1990;97:159-67.

11. Bergersen EO. Enlargement and distortion in cephalometric radiography: Compensation tables for linear measurements. *Angle Orthod* 1980; 50:230-244.
12. Adams JW. Correction of error in cephalometric roentgenograms. *Angle Orthod* 1940;10:3-13.
13. Ghafari J, Cater PE, Shofer FS. Effect of film-object distance on posteroanterior cephalometric measurements: Suggestions for standardized cephalometric methods. *Am J Orthod Dentofac Orthop* 1995;108:30-7.
14. Major PW, Johnson DE, Hesse KL, Glover KE. Effect of head rotation on postero-anterior cephalometric landmark identification. *Angle Orthod* 1996;66:51-60.
15. Ishiguro K, Krogman W, Mazaheri M, Harding R. A longitudinal study of morphological craniofacial patterns via PA x-ray headfilm in cleft palate patients from birth to six years of age. *Cleft Palate* 1974;13:104-126.
16. Ahlqvist J, Eliason S, Wellander U. The cephalographic projection Part II: Principles of image distortion in cephalometry. General considerations. *Dentomaxillofac Radiol* 1983;12:101-108.
17. El Mangoury NH, Shaheen SI, Mostafa YA. Landmark identification in computerized posteroanterior cephalometrics. *Am J Ortho Dentofac Orthop* 1987;91:57-61.
18. Major PW, Johnson DE, Hesse KL, Glover KE. Landmark identification error in posterior- anterior cephalometrics. *Angle Orthod* 1994;64:447-54.
19. Starrett Coordinate Measuring Machine Division. Bulletin No.704;11/1998 5M/S: Pg. 3.

20. Baumrind S, Frantz R. The reliability of head film measurements. 1. Landmark identification. *AM J Orthod* 1971;60(2):111-27.
21. Houston WJB. The analysis of errors in orthodontic measurements. *Am J Orthod* 1983;83:382-90.
22. Richardson A. A comparison of traditional and computerized methods of cephalometric analysis. *Eur J Orthod* 1981;3:15-20.
23. Pirttiniemi P, Miettinen J, Kantomaa T. Combined effects of error in frontal-view asymmetry diagnosis. *Europ J Orthod* 1996;18:629-36.

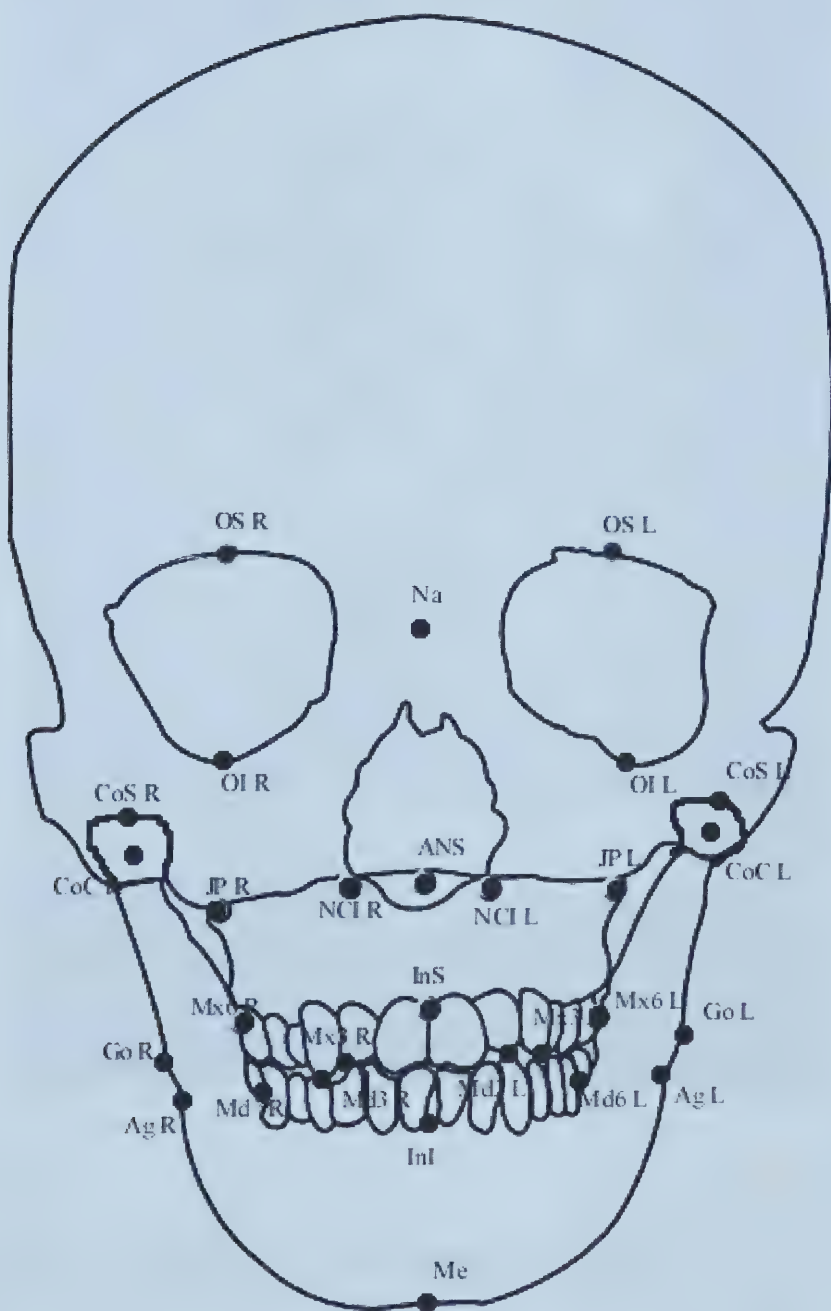


Figure 2.1 Anatomic Landmarks Located with Chromium-steel Markers on the Surface of the Skull



Figure 2.2. Skull Mounted on Custom-made Moving Apparatus



Figure2.3. Skull in Neutral Position. Arrow points to the origin of the Skull Coordinate system (SCS) that was used to measure the location of all Anatomic Landmarks with the Coordinate Measuring Machine (CMM).

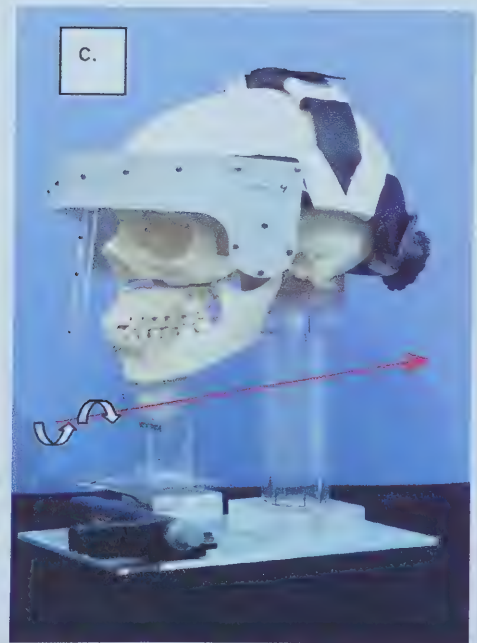
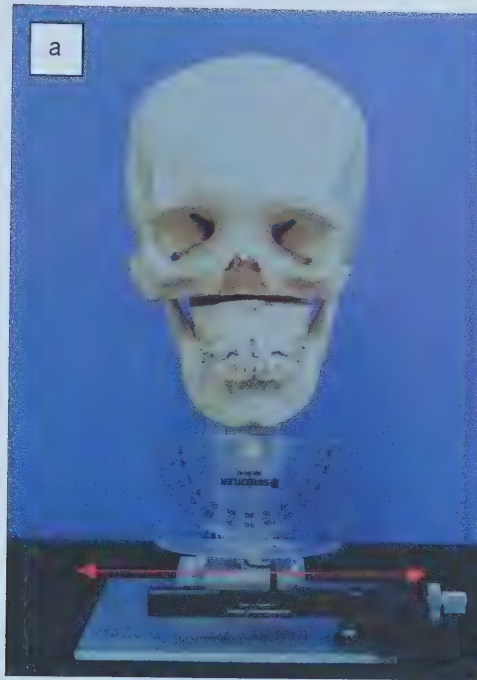


Figure 2.4 a. Skull in Left Translation; b. Skull in Left Vertical Rotation
c. Skull in Left Horizontal Rotation. Arrows show the direction of movement created with the moving apparatus.

CHAPTER III

SECOND RESEARCH STUDY AND RESULTS

ASSESSMENT OF FACIAL ASYMMETRIES FROM POSTERIOR-ANTERIOR CEPHALOGRAMS: VALIDITY OF REFERENCE LINES

3.1 INTRODUCTION

A crucial step in the analysis of asymmetry from PA cephalograms is the selection of reference lines. In choosing reference lines several factors need to be considered. Cranio-facial structures that will be used to draw reference points should be stable, exhibit symmetry and have excellent visibility on the film to facilitate landmark location. Many PA cephalometric analyses of asymmetry use horizontal and vertical reference lines from which subsequent calculations of asymmetry can be completed.¹⁻²⁴ Vertical and transverse asymmetry is measured by comparing corresponding structures from the right and left sides. Midline structures can also be used to assess asymmetry as deviation towards the right or left side from the chosen reference line.

A literature review revealed that a variety of reference lines have been used for analysis of asymmetry. The upper part of the facial skeleton, including the anterior cranial base, has been utilized the most in the construction of horizontal reference lines.^{1,2,6-8,10-12,16,20,21,24}

The anterior cranial base completes its growth earlier than the rest of the face and offers stability required from a reference structure.²⁵ The upper and middle face, including the forehead and orbits, as well as the anterior cranial base, are also the most symmetric regions.¹ The fact that after eight years of age the superior and lateral orbital contours are stable reference areas²⁵ has lead to the frequent use of orbital landmarks in the construction of horizontal reference lines.^{1,2,10,12,20,21,24} The lateral part of the Zygomatico-

Frontal suture has also been used ^{7,8} as well as the center of the Zygomatic arches. ¹⁶ The use of several horizontal reference lines, located in different regions of the face, as opposed to one, has also been advocated for measuring vertical asymmetry. ^{6, 17,18,26}

Vertical reference lines have been constructed in several ways. One method involves drawing a perpendicular through a midpoint of a horizontal line between a pair of bilateral points, ^{5,10,12,17,18} or through a midline anatomical point. ^{1,8,15,16,20} Another method is drawing a vertical line through two midpoints. Such is the vertical line used by Grummons et al., ⁶ who constructed a line between Crista Galli and Anterior Nasal Spine. In cases when these landmarks can not be properly identified the authors proposed using alternate vertical reference lines, constructed between Zygomatico-Frontal points or the centers of the right and left Foramen Rotundum. Cheney ⁴ used a vertical line that passes through Nasion and Anterior Nasal Spine, while Padwa et al. ¹³ constructed a vertical line through Crista Galli and most-superior point on the Nasal Septum.

The Best-fit method ^{3,9,19,23,24} employs the midpoints of multiple pairs of bilateral landmarks or midline landmarks that are used to construct a line by the least-squares method.

There are no studies that have verified the validity of reference lines in representing known facial asymmetries. This lack of knowledge is mainly due to the fact that it is difficult to reliably measure the extent of existing asymmetry. Suggestions have been made that the use of Best Fit Lines could provide the most reliable reference system for PA analysis ²⁴ but there are no studies available to support this assumption. This study was designed with

the objective to examine the ability of various horizontal and vertical reference lines to accurately represent vertical and transverse asymmetries. Another objective was to evaluate whether asymmetry measurements relative to Best Fit reference lines more closely represent true asymmetry than individual point-to-point reference lines.

3.2 MATERIALS AND METHODS

3.2.1 Experimental Design

An experimental three-dimensional model was created using a human dry skull with no visible damage to the maxilla and mandible, and with intact dentition including second molars. Thirty-seven anatomic landmarks were located on the surface of the skull by careful examination and using precise definitions available from the literature (Table 3.1). Of these, 13 were located in the upper cranium, 10 in the maxilla and 14 in the mandible (Figure 3.1) Using a dental slow-speed hand piece and a carbide bur (size 2) shallow semi-spherical concavities were drilled in the skull to mark the location of all landmarks. Chromium-steel markers of 1/16" (1.5875 mm) diameter were fitted tightly into the concavities and glued in place.

The two jaws were occluded following the patterns of attrition and cusp-fossa morphology on the occlusal surfaces. Wire inter-maxillary fixation was used to securely attach the mandible to the maxilla. This maxilio-mandibular unit was then "freed" from the skull by making a cut above the maxillary body as in Le Fort I osteotomy. Both jugal points (JP-R, JP-L) remained a part of the movable maxillo-mandibular complex.

The skull was "centered" into what was termed the initial or "neutral" position (NP). This was achieved by aligning points *Nasion* (Na) Anterior Nasal Spine (ANS), Incisal Superior (InS) and Incisal Inferior (InI). *Menton* (Me) could not be aligned with the rest

of the midpoints without having to rotate the maxillo-mandibular complex and significantly changing the position of both jaws.

A total of thirty asymmetries were created using a custom-made jaw-moving apparatus (Figure 3.2) It incorporated the following three main units:

- a. A metal platform (156 mm x 200mm) that served as a base onto which the skull, the maxillo-mandibular unit and the components of the moving apparatus were mounted.
- b. A skull holder, represented by a cylinder-shaped lucite rod that was attached to the area of foramen magnum at the upper end, and to the platform at the lower end. The skull holder kept the skull with its Frankfort horizontal parallel to the base.
- c. The actual moving apparatus, designed to provide three types of movement:
 - ◆ Translation
 - ◆ Vertical rotation (rotation around a vertical axis)
 - ◆ Horizontal rotation (rotation around a horizontal axis)

The moving apparatus itself consisted of another lucite rod attached to the inferior border of the mandible at the upper end, and fitted into a metal casing at the lower end, which connected onto a microscope stage. The lucite rod with the maxillo-mandibular complex attached at its upper end could be moved sideways along the microscope stage, and could also be rotated around its long axis. The third type of movement was provided by an indirect attachment between the mandible and the upper end of the rod. This piece allowed for the maxillo-mandibular complex to be rotated around a horizontal (anterior-posterior) axis.

To create translational asymmetries, the control dial of the microscopic platform was turned to slide the jaws along the millimetric scale (Figure 3.3a). A total of 10 movements were produced. These consisted of 5 movements towards the skull's right side at 1.5-mm increments (1.5mm, 3mm, 4.5mm, 6mm and 7.5mm) and 5 movements towards the left side, at the same increments.

For vertical rotation, the lucite rod was rotated within its bearing away from the neutral position (NP) towards the right side and left side, respectively. The vertical axis of rotation was represented by a vertical line passing through the centre of the lucite rod. (Figure 3.3 b) These movements were measured using the horizontal protractor that was glued on the rod and set at 90 degrees in the neutral position. A metal pointer marked the neutral position or the centre from which all subsequent vertical offsets were measured on the protractor. Right side rotation (RVR) was defined when the maxillo-mandibular unit was being rotated towards the skull's right side, and the opposite rotation represented left vertical rotation (LVR). On each side, five degrees of movement were recorded at 1.5, 3, 4.5, 6 and 7.5 degrees for a total of 10 rotations.

Horizontal rotation was achieved by rotating the maxillo-mandibular complex around the horizontal axis that passed in an anterior-posterior direction through the length of the rotation screw positioned inferior to the mandible. The jaw complex was rotated towards the right side (right horizontal rotation- RHR), and towards the left side (left horizontal rotation - LHR), at 1.5, 3, 4.5, 6 and 7.5-degrees (Figure 3.3 c). Right horizontal rotation was defined when point Me shifted toward the right side of the skull. Another protractor that was glued onto the small lucite plate immediately below the rotational screw

measured the incremental movement. The neutral position was marked with a line scribed onto the lucite rod, and each rotational movement was measured as an offset from this line.

3.2.2 Measurement of Created Asymmetries

True asymmetries were measured by locating the coordinates of the 24 maxillary and mandibular markers, first in the neutral position, and then their re-location at all created asymmetric positions. (total of 30). This was achieved with the use of a Coordinate Measuring Machine (Starrett^R Premis No. HGC Series Manual, Mount Airy, North Carolina, USA). The CMM has the capability of measuring three-dimensional coordinates of any given point within its measuring range and provides a reading that consists of x-coordinate (transverse axis), y-coordinate (vertical axis) and z-coordinate (anterior-posterior axis). For the purposes of this study the transverse (x) and vertical (y) coordinates of points were used.

The first crucial step before measuring the location of each metal marker from the surface of the skull was to transfer the origin of the CMM coordinate system onto the skull/moving device. This eliminated the need to physically align the skull with the CMM coordinate system. The new skull-coordinate system (SCS) from which all CMM measurements were obtained was created at the left corner-point of the upper edge on the frontal surface of the metal platform (Figure 3.4). After the SCS was created, all markers were located by touching each one individually with the tip of the measuring probe (d=1mm). All measurements were repeated three times.

3.2.3 Posterior-anterior Cephalometric Technique, Digitization Procedure and

Method of Establishing Vertical and Horizontal Reference Lines

The skull with the moving apparatus was placed on a stable flat surface and carefully positioned in the cephalostat of a Siemens cephalometric machine (Siemens Electric Ltd. Bensheim, Germany) for posterior-anterior exposure. The film-source distance was fixed at 130". Several test films were taken to establish a setting that provided radiographs of the best quality (75kV, 6mA and 0.4 sec).

The maxillo-mandibular unit was re-positioned into all previously described types of asymmetries and a PA cephalogram was taken after each change. The total number of PA cephalograms was 31, one exposed in the neutral position, and thirty in the asymmetric movements. Prior to developing the films, each movement was given a 4-digit number code and this number was stamped on the corresponding radiograph.

All PA cephalograms were scanned using a Umax Astra 1200S Scanner at 1200dpi and saved as bitmap files. The image files were digitized by one observer using a custom-made computer digitization program (Ceph Caliper Ltd). The first step of the protocol was to establish the origin of a coordinate system. Points Orbita Superior R and Orbita Superior L were the primary points located by the operator by clicking with the mouse locator on the computer screen. Next, the program used these two points to draw a connecting line between them. A secondary point was established at a fixed distance to the left from the OS L along the connecting line. From this point, another line perpendicular

to the OS line was constructed vertically. The origin of the coordinate system was marked at the same fixed distance along this line. This method allowed for the x-axis of the coordinate system to be parallel with the OS line, and to have an origin in the lower left corner of the radiograph. Once the origin was established, the 24 maxillo-mandibular landmarks as well as the rest of the landmarks marked with metal markers (upper cranial anatomic landmarks) were digitized. In addition, seven radiographic landmarks were also digitized (Table 3.1 and Figure 3.1) Each radiograph was digitized three times by the same operator and on separate occasions.

On every PA cephalogram 10 horizontal and 15 vertical reference lines were constructed. The protocol for establishing these lines was the following:

Horizontal Reference Lines (H-Ref)

I. H-Ref 1= Best fit line

(where best fit horizontal line means that the points (OS L, OM L, FR L, OI L, OL L, GWIO L, GWSO L, ZF L, Z L are used to find a left side average point and their corresponding right side points are used to find an average right side point.

These average points are joined to make the best fit horizontal line).

II. The other nine lines were horizontal lines formed by joining the following left and corresponding right landmarks.

H-Ref 2= OSR-OSL

H-Ref 3= OLR-OLL

H-Ref 4= OIR-OIL

H-Ref 5= OMR-OML

H-Ref 6= ZFR-ZFL

H-Ref 7= GWSOR-GWSOL

H-Ref 8= GWIOR-GWIOL

H-Ref 9= FRR-FRL

H-Ref 10= ZR-ZL

Vertical Reference Lines (V-ref)

These lines were constructed using three methods:

I. V-Ref 1= Best Fit Line

(constructed by averaging the location of all cranial points from the left side and all points from the right side, joining these two points, and constructing a perpendicular line through the midpoint between the two averaged points).

II. The next group were lines constructed between two anatomic points located in the middle of the skull:

V-Ref 2= CG-Na

V-Ref 3=CG-ANS

V-Ref 4=CG-Me

V-Ref 5=Na-ANS

V-Ref 6=Na-Me

Note: CG and Na were stationary points while ANS and Me were located on the moving part of the maxillo-mandibular unit

III. The third group were lines made by joining bilateral analogue points from the right and left side, finding the midpoint between them, and drawing a perpendicular line through that midpoint. The following points were used to construct perpendicular lines:

V-Ref 7=FR Perp

V-Ref 8=GWSO Perp

V-Ref 9=GWIO Perp

V-Ref 10=OS Perp

V-Ref 11=OL Perp

V-Ref 12=OI Perp

V-Ref 13=OM Perp

V-Ref 14=ZF Perp

V-Ref 15=Z Perp

Further, on every PA cephalogram the location of each of the 24 maxillo-mandibular landmarks was measured as the transverse ($X\perp$) and vertical ($Y\perp$) perpendicular distance from the landmark to the 10 horizontal and 15 vertical reference lines (Figure 4). These values were signed to represent location of the point relative to the reference lines. If a point was located above the horizontal reference line it received a negative sign, and if it was on the left side of the vertical line the value was negative. All measurements were expressed in millimetres.

3.2.4 Method Error

The total error of measurement in the study could result from the following factors:

1 Accuracy of the CMM

- 2 Error due to intra-observer variability when locating landmarks with CMM
- 3 Error due to moving apparatus (MA)
- 4 Error due to intra-observer variability when locating landmarks with computer-aided digitization

The linear accuracy of the CMM is 0.0038 mm per axis as reported by the manufacturer.

²⁷ It is thoroughly inspected and calibrated at the time of instalment with equipment that is traceable to the US National Institute of Standards and Technology.

The intra-observer reproducibility in locating the markers with the CMM was tested in a pilot study, by repeated measurement of six point-to-point distances between randomly selected markers on five occasions. Two distances were measured on the upper cranium (N-ZFL, OSR-OIR), two on the maxilla (JL-ANS, InS-Mx6L) and two on the mandible (CoSL-InI, AgL-AgR).

The repeatability of the moving apparatus (MA) was also tested in a pilot study. Five asymmetric movements were created with the apparatus and the x, y and z coordinates of five randomly chosen landmarks (ANS, JR, Mx6 R, InI and Me) at each movement were recorded with the CMM. The same protocol was used on five occasions. The error of repeated measurement was then calculated for each landmark with the following formula:

Error between first and second measurement = square root $((x1-x2)^2 + (y1-y2)^2 + (z1-z2)^2)$

The same formula was used to calculate the differences between the first and third, the

first and fourth, and first and fifth measurement. These values were then used to calculate a mean, maximum, minimum and standard deviation of error due to MA.

Investigator bias during the digitization process was eliminated by coding the PA cephalograms with random numbers. The investigator had no knowledge of the type of movement each cephalogram represented. Landmark identification error in this study was reduced by the use of spherical chromium-lead markers. The center of the radiographic image of the markers was the digitizing target. All radiographs were digitized on three separate occasions, and the repeated measure error was calculated for each landmark using the following formula:

Error between first and second digitization = square root $((x_1-x_2)^2+(y_1-y_2)^2)$

The same formula was used to calculate the differences between the second and third, and the first and third digitization for each radiograph. These three values from all radiographs were used to provide a mean error, standard deviation of the mean error and mean of the standard deviation of the mean error as indicators of total digitization error.

3.2.5 Statistical Analyses

The CMM data was used to provide a measure of true asymmetry achieved during the 30 movements. The increment of change in position of the individual maxillo-mandibular landmarks was calculated by subtracting the measured location of the point in the neutral position from the measured location in the asymmetric position. For example: CMM

measurement for point CoC R in the neutral position (NP) was x-coordinate = 33.71 mm and y-coordinate = 176.53 mm. In right horizontal rotation (RHR) 7.5 degrees, the values measured for CoC R were x-coordinate = 24.38 mm and y-coordinate = 182.36 mm. The increment of asymmetry for CoC R at RHR 7.5 degrees would be:

$$\text{CoC R } \Delta X (\text{RHR } 7.5) = X(\text{RHR } 7.5) - X(\text{NP}) = 24.38 - 33.71 = -10.67 \text{ mm}$$

$$\text{CoC R } \Delta Y (\text{RHR } 7.5) = Y(\text{RHR } 7.5) - Y(\text{NP}) = 182.36 - 176.53 = +5.83 \text{ mm}$$

The same increments of change obtained for CoC L at RHR 7.5 would be:

$$\text{CoC L } \Delta X (\text{RHR } 7.5) = +9.95 \text{ mm and}$$

$$\text{CoC L } \Delta Y (\text{RHR } 7.5) = -4.78 \text{ mm.}$$

In the case of bilateral landmarks total vertical and transverse asymmetry were calculated as the difference in increments of change between the right and left sides. In the example given, total transverse asymmetry for CoC at RHR 7.5 degrees would be:

$$\text{CoC transverse asymmetry} = \text{CoC R } \Delta X (\text{RHR } 7.5) - \text{CoC L } \Delta X (\text{RHR } 7.5) = -10.67 - (+9.98) = -20.65 \text{ mm}$$

$$\text{CoC vertical asymmetry} = \text{CoC R } \Delta Y (\text{RHR } 7.5) - \text{CoC L } \Delta Y (\text{RHR } 7.5) = +5.83 - (-4.78) = +10.61 \text{ mm}$$

For the midline points ANS, InS, InI, and Me, the actual ΔX and ΔY were used as measures of asymmetry.

Radiographic asymmetries were determined in the same manner as true asymmetries, i.e. as changes in location of each landmark from the neutral to the 30 asymmetric positions. The calculations were performed with the perpendicular distances from the landmarks (X_{\perp} and Y_{\perp}) to each of the 10 horizontal and 15 vertical reference lines. On each PA cephalogram the ΔX_{\perp} and ΔY_{\perp} for each landmark were calculated relative to the individual lines. The total vertical and transverse asymmetry measures for every pair of bilateral landmarks were further calculated as differences between the increments of change ($\Delta X_{\perp R} - \Delta X_{\perp L}$ and $\Delta Y_{\perp R} - \Delta Y_{\perp L}$) from the right and the left sides.

Ten linear regression analyses were performed using the measures of true vertical asymmetry for all pairs of landmarks and midline landmarks as the independent variable, and the vertical radiographic asymmetry measures obtained relative to the ten horizontal reference lines as the dependent variable. True transverse asymmetry was the independent variable for 15 linear regression analyses, while the dependent variable was radiographic transverse asymmetry obtained from each of the 15 vertical reference lines.

3.3 RESULTS

Intra-observer reproducibility of measurement with the CMM was adequate (Table 3.2). The range of standard deviations of repeated measurements was between 0.09 and 0.58 mm.

The MA reproducibility error ranged between 0.36 ± 0.22 to 0.87 ± 0.39 mm (Table 3.3). The reproducibility of the moving apparatus was deemed acceptable since the error was smaller than the smallest increment of change created with the apparatus (1.5 mm).

The error of locating landmarks with CMM was also small. The range of error was between 0.14 ± 0.05 mm for right Nasal Cavity Inferior to 0.63 ± 0.3 mm for right Maxillary Molar (Table 3.4).

Results from intra-observer reproducibility of landmarks digitizations are presented in Table 3.5. The three values presented are the mean error, the standard deviation of the mean error, and the mean of the standard deviations of repeated landmark identification. Among the 37 landmarks that were marked with metal markers intra-observer reproducibility was the best for Orbita Superior Right (0.16 ± 0.12 mm). The largest error was observed for right maxillary cuspid (0.6 ± 0.29 mm). Radiographic landmarks displayed similar reproducibility error. Crista Galli and Greater Wing Superior Orbit had error larger than 1mm (0.65 ± 0.31 and 0.56 ± 0.25 mm respectively), while Foramen Rotundum Left had the smallest error (0.29 ± 0.12 mm).

Results from the linear regression analyses between true vertical asymmetry and radiographic vertical asymmetry measured relative to the 10 horizontal reference lines are presented in Table 3.6. Table 3.7 contains the linear regression results of transverse asymmetries measured relative to the 15 vertical reference lines. The association between the 3D and 2D data is expressed by the three indicators included in the tables (adjusted R^2 , constant and slope). The adjusted R^2 values are an overall measure of the linear relationship, or the goodness-of-fit, between the 3D and 2D data. When multiplied by 100 they express the percentage of the variability in the 3D data that is explained by the 2D data. The constant and the slope are the parameters that describe the linear relationship between the tested variables. For an ideal fit of the regression line, the constant should be zero, and the slope should be one.

The adjusted R^2 values for all horizontal reference lines were high, indicating excellent correlation between true asymmetry and vertical asymmetry measured to the 10 lines (Table 3.6). Highest adjusted R^2 value was achieved by the Horizontal Best Fit line (0.969 or 96.9 %). The constant was close to zero only in the case of OI horizontal reference line, signifying that asymmetry measured to this line was most accurate.

In Table 3.7 the adjusted R^2 values were excellent for ten reference lines. Nine of these lines were the perpendiculars to a midpoint between pairs of cranial landmarks. The Vertical Best Fit line ranked second according to the adjusted R^2 value. Four reference lines had constants that were close to zero, ZF-Perp, OI Perp, OL Perp and OM Perp. The slope was close to 1 for the 10 reference lines. The five reference lines that were drawn

between two anatomical points showed less agreement with true asymmetry than the perpendicular lines and the best fit line. The poorest correlation between true asymmetry and radiographic asymmetry was obtained when CG-ANS reference line was used (adjusted $R^2 = 0.058$ or 0.5%).

3.4 DISCUSSION

The dry skull model was used to create 30 known maxillo-mandibular asymmetric changes, and to accurately measure the increments of change with a coordinate measuring machine (CMM). Particular attention was given to controlling the error of measurement. As reported in Tables 3.2 to 3.4 the error of the method was acceptable. The values obtained for increments of change were used as the gold standard to determine the validity of various reference lines for measuring asymmetry .

Landmark identification error was minimized in this study by the use of metal markers. The error introduced by locating landmarks on the PA cephalograms is the largest source of error in cephalometry.^{28 -30} Although it was not possible to mark the radiographic landmarks, the error of repeated digitizations of these landmarks was similar in range to that of marked landmarks (Table 3.5). In addition, one observer performed all digitizations, since most studies report that intra-observer error is smaller than inter-observer error.^{30, 31} Studies that have evaluated error in PA cephalometry report a characteristic envelope of error for each landmark along the x and y coordinates.^{31,32} The total error of landmark identification in this study includes the error along both axes. It is not possible to directly compare the landmark identification error in this study with previous research. The digitization error for all landmarks, except for Me, Mx 3 R / L, CG and GWSO R, was smaller than 1 mm, which is considered excellent reproducibility.

The use of chromium-steel markers improved landmark identification reproducibility, but in clinical practice many factors can affect landmark identification. These include the quality of the cephalogram, the visibility of the landmarks on the film, and the operator's experience.³¹ The results of this study should serve as a general guideline when deciding which reference lines to use for PA analysis, but the ultimate choice should be made upon published data on landmark identification error. Landmarks with a large vertical identification error should be avoided in the construction of horizontal reference line. Similarly, landmarks with large horizontal error should not be used in the construction of vertical reference line.

All horizontal reference lines provided valid measurements of vertical asymmetry (Table 3.6). These findings support the use of any of these lines in PA analysis. Measurements relative to Orbita Inferior horizontal reference line were most accurate. However, the vertical identification error of Orbitale Inferior is reportedly large³¹ and this line might not be most adequate for measuring true vertical asymmetry. Other points with significant identification error are Orbitale Medial, Zygomatico Frontal and Foramen Rotundum.³¹

Our results showed that vertical lines connecting two midpoints are not reliable for transverse measurements. In particular, vertical lines drawn between Crista Galli and Anterior Nasal Spine, or Nasion and Anterior Nasal Spine had very low validity. One of the more commonly used PA cephalometric analysis uses CG-ANS as a vertical reference line.⁶ Based on the findings of this study CG-ANS should not be used as a vertical reference line. The reason these lines are unable to adequately represent asymmetric changes could be that one of the two points (ANS or Me) was located on structures that

were involved in the asymmetric manipulations, and were not stable to provide adequate reference. However, Crista Galli-Nasion line was also inaccurate, although both points were stationary and therefore stable reference points. The proximity of CG and Na could have been a factor in the poor outcome for this line. Vertical separation between two midpoints that will be used to draw a vertical line has been recommended.²⁴

The most valid vertical reference lines in this study were drawn as perpendiculars to horizontal lines between bilateral cranial landmarks (Table 3.7). A perpendicular line has been used as a vertical reference line by a number of authors.^{5,10,12,17,18} The four vertical lines that had high adjusted R^2 values but also had constants close to zero (ZF Perp, OI Perp, OL Perp and OM Perp) might provide most accurate measurements of true transverse asymmetric changes. However, landmark identification error of Zygomatico Frontal points, Orbitale Inferior, and Orbitale Medial could be large.³¹ If a significant landmark identification error is made these vertical reference lines will not be the best lines to use.

It has been suggested that a Best Fit line may be more accurate than other reference lines because of the self-correcting feature incorporated in the method.^{3,9,19,23,24} Namely, when multiple landmarks are located, the point(s) that are obviously off in relation to the other points of the cranium and face can be excluded when drawing the axis. Although the Best Fit lines ranked high according to R^2 values, the magnification factors did affect measurements to these lines (Tables 3.6 and 3.7). For practical purposes, the construction of a Best Fit line is more involved than the construction of a line through two points, or drawing a perpendicular line. Therefore, the use of a Best Fit Line is not necessary.

Rotations within the cephalostat were eliminated in this study by using a custom-made head-holder and exposing all PA films without removing the skull from the cephalostat. Reproducible patient positioning cannot always be achieved in practice. Rotations of the patient in the cephalostat around the horizontal (trans-meatal) axis up to 5 degrees have been reported to have no effect on the transverse or vertical location of landmarks on PA films,^{34,35} while rotations about the vertical axis do affect transverse measurements.³⁵ If more significant rotations take place it cannot be expected that the validity of PA reference lines will be clinically acceptable. Johnston²⁴ investigated the effects of error due to head rotations upon reference lines and concluded that the most appropriate horizontal reference line was the line between GWSO R and L. The results of our study support the use of GWSO horizontal reference line in PA analysis.

This study included one skull that was randomly chosen for the experiment. There was no apparent asymmetry or deformity of the cranial structures, and it was assumed that the skull featured normal anatomic proportions. However, variations in skull morphology could alter the validity of reference lines. A future study should include more than one skull in order to provide answers to these questions.

3.5 CONCLUSIONS

1. All horizontal lines connecting bilateral cranial landmarks can adequately serve as reference lines in the analysis of vertical asymmetry from PA cephalograms, provided landmark identification error is minimal.
2. The best vertical reference lines are perpendiculars to horizontal lines connecting bilateral cranial landmarks. Any of the commonly used bilateral cranial landmarks can be used in the construction of the vertical line, provided landmark identification error is minimal.
3. Vertical lines connecting two midpoints should not be used as reference lines in cephalometric analysis of transverse asymmetries. In particular, vertical reference lines through Anterior Nasal Spine have low validity if positional changes occur in the midface.
4. Horizontal and Vertical Best Fit Lines are reliable reference lines to use. However, considering the complex way of construction of these lines, it is more practical to use alternate reference lines.

Table 3.1. List of Landmarks. Surface Anatomic Landmarks located with Spherical Metal Markers on the Surface of the Skull; Radiographic Landmarks located on Posterior-anterior Cephalograms in Addition to Surface Anatomic Landmarks

Surface Anatomic Landmarks

Cranial Landmarks

Na	Nasion- the point of contact between the frontal bone and the suture between the two halves of the nasal bones
OS R/L	Orbitale Superior- the midpoint of the superior orbital margin, right and left
OM R/L	Orbitale Medial – the midpoint of the medial orbital margin, right and left
OI R/L	Orbitale Inferior- the midpoint of the inferior orbital margin, right and left
OL R/L	Orbitale Lateral- the midpoint of the lateral orbital margin, right and left
Z R/L	Zygomatic- the most lateral aspect of the zygomatic arch, right and left
ZF R/L	Zygomatic Frontal- the intersection of the zygomatic-frontal suture and the lateral orbital margin, right and left

Maxillary landmarks

ANS	Anterior nasal spine- the centre of the intersection of the nasal septum and the spine
InS	Incisor point Superior- the crest of the alveolus between the upper incisors
NCI R/L	Nasal Cavity Inferior- the lowermost point on the inferior curvature of the nasal cavity
JP R/L	Jugal Point- the deepest point on the curve of the malar process of the maxilla
Mx6 R/L	Maxillary first molar- the midpoint of the buccal surface of the maxillary first molar
Mx3 R/L	Maxillary cuspid- the tip of the maxillary cuspid right and left

Mandibular landmarks

InI	Incisor point Inferior- the crest of the alveolus between the lower incisors
Me	Menton- the midpoint on the inferior border of the mental protuberance
CoS R/L	Condyle Superior- the most superior aspect of the mandibular condyle
CoC R/L	Condyle Center- the center of the mandibular condyle

Ag R/L	Antegonion- the deepest point on the curvature of the antegonial notch
Go R/L	Gonion-the midpoint on the curvature at the angle of the mandible right and left
Md6 R/L	Mandibular first molar- the midpoint of the buccal surface of the mandibular first molar right and left
Md3 R/L	Mandibular cuspid- the tip of the mandibular cuspid right and left

Radiographic Anatomic Landmarks

CG	Crista Galli- the uppermost point on crista galli
GWSO R/L	Greater Wing Superior Orbit- the intersection of the superior border of the greater wing of the sphenoid bone and the lateral orbital margin, right and left
GWIO R/L	Greater Wing Inferior Orbit-the intersection of the inferior border of the greater wing of the sphenoid bone and the lateral orbital margin, right and left
FR R/L	Foramen Rotundum-the centre of the foramen rotundum, right and left

Table 3.2. Intra-observer reproducibility in Measuring Landmark Position with Coordinate Measuring Machine (CMM): Five times Repeated Measures of Five Randomly Selected Distances between Metal Markers on the Skull Surface (in mm).

Distances						
<u>Occasion</u>	<u>N-ZFL</u>	<u>OSR-OIR</u>	<u>JL-ANS</u>	<u>InS-Mx6L</u>	<u>CoSL-InI</u>	<u>AgL-AgR</u>
1.00	49.83	33.65	44.21	20.22	106.60	67.27
2.00	49.73	33.76	44.26	20.52	106.98	67.06
3.00	49.78	33.85	44.32	20.41	107.08	66.99
4.00	49.70	32.52	44.09	19.93	106.60	67.25
5.00	49.93	33.94	43.68	20.03	106.99	67.25
Mean	49.79	33.55	44.11	20.22	106.85	67.16
SD	0.09	0.58	0.25	0.25	0.23	0.13

Table 3.3. Reproducibility of Moving Apparatus (MA): Error of Measurement Due to Five Times Repeated Measure of Five Selected Points. Means, Standard Deviations, Maximum and Minimum Values of Differences between the First and Subsequent Four Repeated Measures (in mm).

<u>Statistics</u>	<u>ANS</u>	<u>JPR</u>	<u>Mx6L</u>	<u>InI</u>	<u>Me</u>
Mean	0.87	0.46	0.47	0.77	0.71
SD	0.07	0.24	0.08	0.20	0.26
Max	0.95	0.81	0.56	0.92	1.03
Min	0.77	0.27	0.39	0.49	0.49
Mean	0.63	0.53	0.55	0.87	0.62
SD	0.31	0.20	0.17	0.39	0.22
Max	0.91	0.69	0.70	1.26	0.84
Min	0.20	0.24	0.32	0.33	0.31
Mean	0.73	0.81	0.33	0.85	0.78
SD	0.21	0.13	0.06	0.20	0.08
Max	0.95	0.99	0.40	1.07	0.88
Min	0.53	0.70	0.27	0.63	0.68
Mean	0.62	0.78	0.36	0.46	0.44
SD	0.11	0.20	0.22	0.15	0.28
Max	0.77	0.95	0.66	0.68	0.85
Min	0.50	0.50	0.18	0.36	0.21
Mean	0.85	0.50	0.70	0.47	0.52
SD	0.18	0.24	0.20	0.20	0.15
Max	1.00	0.83	0.81	0.78	0.65
Min	0.63	0.31	0.40	0.35	0.30

Table 3.4. Intra-observer Error of Repeated Measurement with Coordinate Measuring Machine (CMM) (in mm).

<u>Landmark</u>	<u>Mean*</u>	<u>SD of mean</u>	<u>Mean of</u> <u>SD</u>
AgL	0.24	0.09	0.11
AgR	0.21	0.11	0.09
ANS	0.23	0.15	0.11
CoCL	0.15	0.05	0.05
CoCR	0.20	0.07	0.07
CoSL	0.16	0.07	0.07
CoSR	0.18	0.07	0.08
GoL	0.25	0.13	0.13
GoR	0.23	0.20	0.13
InI	0.20	0.08	0.08
InS	0.16	0.07	0.07
JPL	0.25	0.14	0.13
JPR	0.21	0.10	0.10
Md3L	0.35	0.23	0.16
Md3R	0.39	0.19	0.18
Md6L	0.16	0.06	0.07
Md6R	0.22	0.13	0.11
Me	0.40	0.20	0.18
MX3L	0.63	0.14	0.30
Mx3R	0.31	0.10	0.15
Mx6L	0.21	0.10	0.10
Mx6R	0.22	0.10	0.10
NCIL	0.16	0.07	0.07
NCIR	0.14	0.06	0.05

Table 3.5. Intra-observer Error (in mm) of Computer-aided Location of All Anatomic Landmarks, Including Surface Landmarks (Marked with Chromium-steel Markers) and Radiographic Landmarks.

Landmark	Mean Error	SD of mean error	Mean of SD	Total Error
Surface landmarks				
AgL	0.50	0.21	0.23	0.94
Ag-R	0.49	0.25	0.22	0.96
ANS	0.33	0.14	0.13	0.59
CoCL	0.35	0.15	0.17	0.67
CoCL	0.34	0.14	0.14	0.61
CoC-R	0.33	0.14	0.17	0.65
CoSR	0.35	0.14	0.15	0.64
GoL	0.50	0.21	0.24	0.95
Go-R	0.47	0.20	0.21	0.87
InI	0.42	0.21	0.21	0.84
InS	0.37	0.13	0.16	0.66
JPL	0.36	0.18	0.18	0.71
JP-R	0.40	0.27	0.19	0.85
Md3L	0.39	0.13	0.20	0.72
Md3R	0.43	0.19	0.25	0.88
Md6L	0.43	0.19	0.21	0.83
Md6R	0.44	0.17	0.20	0.81
Me	0.55	0.24	0.25	1.04
Mx3L	0.52	0.26	0.24	1.01
Mx3R	0.60	0.32	0.29	1.21
Mx6L	0.44	0.19	0.20	0.82
Mx6R	0.43	0.19	0.19	0.81
N	0.31	0.10	0.13	0.55

NCIL	0.36	0.17	0.19	0.72
NCI-R	0.34	0.13	0.16	0.64
OI R	0.31	0.15	0.15	0.61
OI L	0.28	0.14	0.16	0.58
OL R	0.32	0.13	0.14	0.59
OL L	0.38	0.15	0.16	0.69
OM R	0.22	0.11	0.12	0.45
OM L	0.23	0.12	0.12	0.47
OS R	0.16	0.08	0.12	0.36
OS L	0.00	0.00	0.00	0.00
Z R	0.39	0.17	0.17	0.73
Z L	0.41	0.16	0.21	0.78
ZF R	0.29	0.13	0.12	0.54
ZF L	0.36	0.13	0.16	0.65
Radiographic				
Landmarks				
CG	0.65	0.29	0.31	1.26
FR R	0.34	0.13	0.15	0.62
FR L	0.29	0.10	0.12	0.51
GWIO R	0.46	0.20	0.24	0.90
GWIO L	0.50	0.17	0.21	0.88
GWSO R	0.56	0.23	0.25	1.04
GWSO L	0.46	0.17	0.20	0.83

Table 3.6. Horizontal Reference Lines. Regression Analysis Results. Reference Lines Sorted According to Adjusted R², from Highest (Expressing Greatest Agreement Between Asymmetry in Truth and Measured Relative to Reference Line on PA films) to Lowest.

**Horizontal
Reference
Lines**

	Adjusted R ²	Constant	p-value of the constant	Slope
Best Fit	0.969	0.128	0.000	0.984
OI	0.967	0.005	0.034	0.983
Z	0.967	0.191	0.000	0.983
ZF	0.967	0.255	0.000	0.983
OL	0.966	0.238	0.000	0.983
GWSO	0.965	0.268	0.000	0.982
OS	0.964	0.167	0.000	0.982
GWIO	0.958	0.225	0.000	0.979
OM	0.953	0.141	0.000	0.976
FR	0.935	0.663	0.000	0.967

Table 3.7. Vertical Reference Lines: Regression Analysis Results. Reference Lines Sorted According to Adjusted R², from Highest (Expressing Greatest Agreement between Asymmetry in Truth and Measured Relative to the Reference Line on PA films) to Lowest.

Vertical Reference Lines	Adjusted R ²	Constant	p-value of the Slope constant	
Z Perp	0.976	-0.169	0.000	0.988
Best Fit	0.975	-0.157	0.000	0.987
ZF Perp	0.975	-0.001	0.677	0.987
GWSO Perp	0.974	-0.219	0.000	0.987
OI Perp	0.974	0.004	0.147	0.987
OL Perp	0.973	-0.002	0.385	0.986
OS Perp	0.973	-0.31	0.000	0.986
FR Perp	0.972	-0.119	0.000	0.986
GWIO Perp	0.967	-0.356	0.000	0.983
OM Perp	0.966	0.008	0.012	0.983
N-Me	0.816	0.001	0.811	0.903
CG-Me	0.788	0.004	0.506	0.888
CG-N	0.695	-0.999	0.000	0.834
N-ANS	0.076	-0.133	0.503	-0.278
CG-ANS	0.058	-0.157	0.382	-0.243

References

1. Alavi D, BeGole E, Schneider BJ. Facial and dental arch asymmetries in CI II subdivision malocclusion. *Am J Orthod Dentofac Orthop* 1988;93:38-46.
2. Buttow KW, van der Walt PJ. The “Stellenbosch”-triangle analysis of the postero-anterior and basilar cephalograms. *J Dent Assoc South Africa* 1981;36:461-7.
3. Chebib FS, Chamma AM. Indices of craniofacial asymmetry. *Angle Orthod* 1981;51:214-26.
4. Cheney EA. Dentofacial asymmetries and their clinical significance. *Am J Orthod* 1961;47:814-29.
5. Fisher B. A study of methods of establishing a mid-sagittal plane in posterior-anterior cephalograms. Master's Thesis, Western Reserve University, 1964.
6. Grummons DC, Kappeyne van de Coppelo MA. A Frontal Asymmetry Analysis. *JCO* 1987;21:448-65.
7. Gugino CF. *Ortho Philosophy* 1977.
8. Harvold EP, Trugue M, Vilorio JO. Establishing the median plane in posteroanterior cephalograms.
9. Hewitt AB. A radiographic study of facial asymmetry. *Brit J Orthod* 1974;2:37-40.
10. Laspos CP, Kyrkanides S, Tallents RH, Moss ME, Subtelny JD. Mandibular and Maxillary Asymmetry in individuals with unilateral cleft lip and palate. *Cleft Palate-Craniofac J* 1997;34 (3): 232-9.

11. Lund K. Mandibular growth and remodelling processes after condylar fracture. A longitudinal roentgencephalometric study. Academic dissertation. Acta Odontol Scand 1974;32:suppl. 64.
12. Molsted K, Dahl E. Asymmetry of the maxilla in children with complete unilateral cleft lip and palate. Cleft Palate 1964;27(2):184-92.
13. Padwa BL, Kaiser M, Kaban LB. Occlusal cant in the frontal plane as reflection of facial asymmetry. J Oral Maxillofac Surg 1997;55:811-6.
14. Peck S, Peck L, Kataja M. Skeletal asymmetry in esthetically pleasing faces. Angle Orthod 1990;61:43-8.
15. Pirttiniemi P, Kantomaa T, Lahtela P. Relationship between craniofacial and condyle path asymmetry in unilateral cross-bite patients. Europ J Orthod 1990;12:408-13.
16. Ricketts RM, Roth RH, Chaconas SJ, Schulhof RJ, Engel GA. Orthodontic Diagnosis and Planning. Denver: Rocky Mountain Data Systems, 1982.
17. Sassouni V. The face in five dimensions. West Virginia University, Morgantown, 1960.
18. Sassouni V, Forrest EJ. Orthodontics in Dental Practice. Saint Louis, C.V. Mosby Company, 1971
19. Shah SM, Joshi MR. An assessment of asymmetry in the normal craniofacial complex. Angle Orthod 1978;48:141-8.
20. Stabrun AE. Mandibular morphology and position in juvenile rheumatoid arthritis. A study on posterior-anterior radiographs. Europ J Orthod 1985;7:288-98.
21. Svanholt P, Solow B. Assessment of midline discrepancies on the posterior-anterior cephalometric radiograph. Trans Europ Orthod Soc 261-277, 1977.

22. Thompson JR. Asymmetry of the face. JADA 1943;30:1859-71.
23. Vig PS, Hewitt AB. Asymmetry of the human skeleton. Angle Orthod 1978;48:141-8.
24. Johnston DE. The posteroanterior cephalometric radiograph. Masters Thesis 1991:pp46.
25. Ranley DM. A Synopsis of Craniofacial Growth. Connecticut: Appleton & Lange, 1988.
26. Proffit Wr, White RP. Surgical -Orthodontic Treatment. St. Louis: Mosby; 1990
27. Starrett Coordinate Measuring Machine Division. Bulletin No.704;11/1998 5M/S: Pg. 3.
28. Savara, BS, Tracy WE, Miller PA. Analysis of errors in cephalometric measurements of three dimensional distances on the human mandible. Arch Oral Biol 1966;11:209-217.
29. Houston WJB. The analysis of errors in orthodontic measurements. Am J Orthod 1983;83:382-390.
30. Gravely JF, Benzies PM. The clinical significance of tracing error in cephalometry. Br J Orthod 1984;11:44-48.
31. Major PW, Johnson DE, Hesse KL, Glover KE. Landmark identification error in posterior- anterior cephalometrics. Angle Orthod 1994;64:447-54.
32. El Mangoury NH, Shaheen SI, Mostafa YA. Landmark identification in computerized posteroanterior cephalometrics. Am J Ortho Dentofac Orthop 1987;91:57-61.
33. Richardson A. A comparison of traditional and computerized methods of cephalometric analysis. Eur J Orthod 1981;3:15-20.

34. Ghafari J, Cater PE, Shofer FS. Effect of film-object distance on posteroanterior cephalometric measurements: Suggestions for standardized cephalometric methods. *Am J Orthod Dentofac Orthop* 1995;108:30-7.
35. Major PW, Johnson DE, Hesse KL, Glover KE. Effect of head rotation on postero-anterior cephalometric landmark identification. *Angle Orthod* 1996;66:51-60.

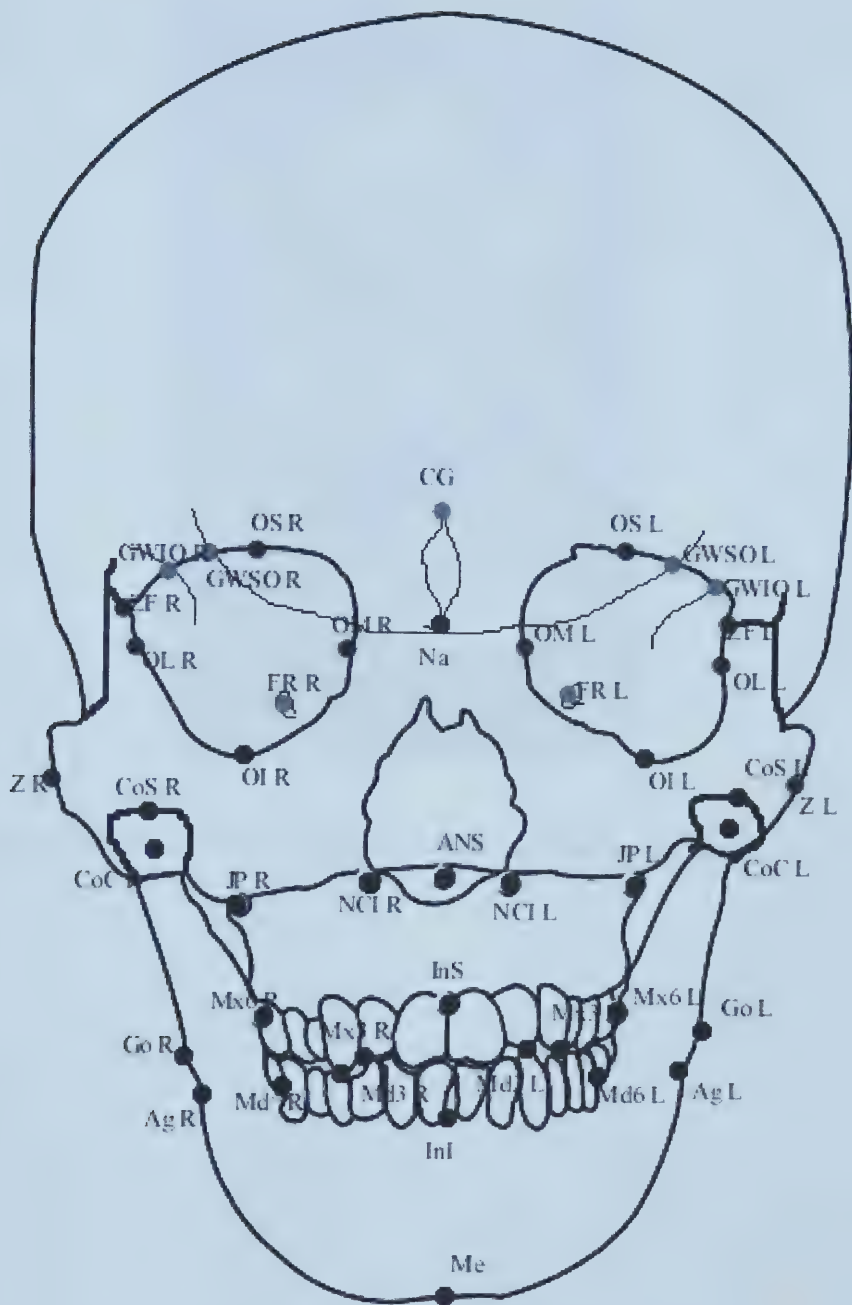


Figure 3.1 Anatomic Landmarks Including Surface Landmarks and Radiographic Landmarks



Figure 3.2 Skull Mounted on a Custom-made Moving Apparatus

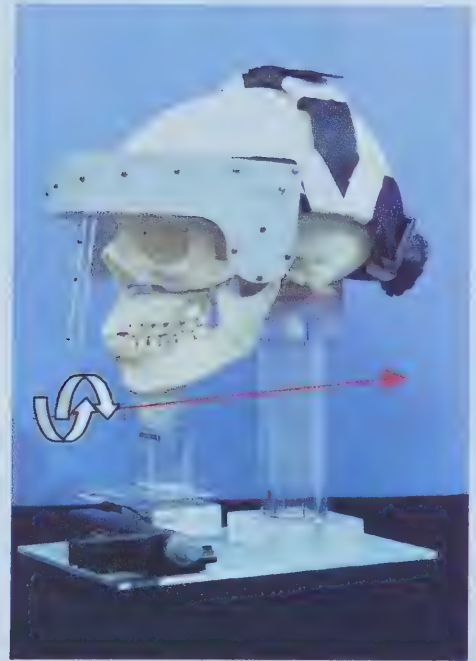
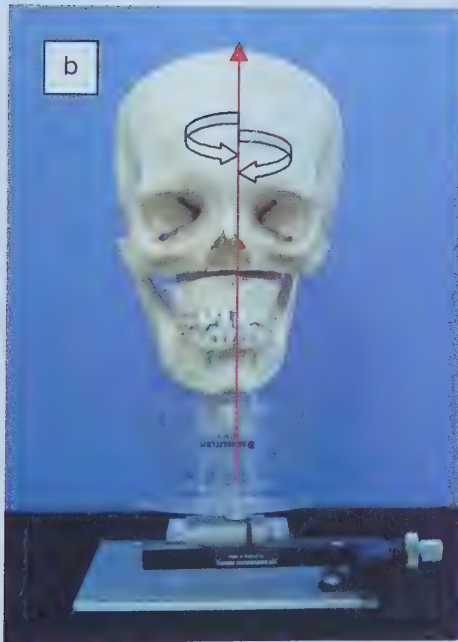
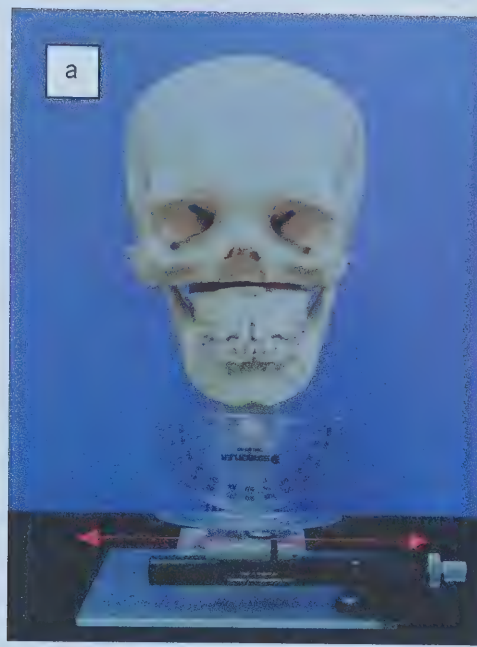


Figure 3.3 a. Skull in Left Translation; b. Skull in Left Vertical Rotation
c. Skull positioned for Horizontal Rotation.
Arrows show the direction of movements created with the moving apparatus.



Figure 3.4. Skull in Neutral Position. The arrow Points to the Origin of the Skull Coordinate System.

CHAPTER IV

GENERAL DISCUSSION AND
RECOMMENDATIONS

4.1 GENERAL DISCUSSION

The first goal of this research was to evaluate the validity of commonly used posterior-anterior (PA) cephalometric landmarks for analysis of dento-facial structures from PA cephalograms. Validity in this study was defined as the ability of anatomic landmarks to display the location of the structures they represent on PA cephalograms. Validity is one of many sources of cephalometric error. Other sources of error have been investigated previously. These include quality of the images,^{1,2} projection errors³⁻⁹, subject positioning¹⁰⁻¹³, repeat imaging¹⁴⁻¹⁶, and landmark identification error.¹⁷⁻²⁰ However, this is the only study to date that has been designed to establish the validity of commonly used cephalometric landmarks in PA cephalometry.

The second goal of this study was to determine the validity of various horizontal and vertical reference lines used for PA cephalometric analysis. Calculations of asymmetric jaw positions were made from measurements between PA cephalometric landmarks and individual reference lines. These values were compared with the known measures of asymmetries from the three-dimensional data. The reference lines that were investigated have been previously used in published PA cephalometric analyses.²¹⁻³²

Validity has been defined as "the extent to which, in the absence of measurement error, the value obtained actually represents the object of interest".¹⁰ The entire experiment was designed to minimize potential sources of error. The first step was to reduce landmark

identification error, being the largest source of error in cephalometry.^{10, 16, 17} Small chromium-steel markers were glued in place of the anatomic landmarks on the surface of the dry skull in order to provide stable references for measurement of the position of all landmarks under study. Even so, since the diameter of the markers was 1.58 mm the possibility of committing measurement error could not be ignored. Thus, intra-observer reproducibility was an essential consideration since all measurements were conducted by one observer. The following steps of the experiment were identified as potential sources of error:

1. observer reproducibility when using the moving apparatus
2. intra-observer reproducibility of locating metal markers with CMM
3. intra-observer reproducibility of locating markers on the PA cehalograms

Appropriate reproducibility tests were completed prior to conducting the actual experiment to determine the range of measurement error for each of these steps. Intra-observer measurement error was small and deemed acceptable to proceed.

The main advantage of this experiment was that the investigator was able to reproducibly manipulate the maxillo-mandibular complex using the custom-made apparatus and to create a series of known deviations of the jaws. At the same time, the rest of the cranio-facial structures remained undisturbed. This was important to ensure stable skull location for the cephalometric exposures and avoid positioning error. The locations of the landmarks at each asymmetric position were accurately measured with the coordinate-measuring machine (CMM). In this way the three-dimensional positions of all anatomic landmarks were calculated as the increments of change from the initial jaw position to each created manipulation. These values were virtually free of measurement error and

could be considered the landmarks' true location relative to their initial position. The same jaw manipulations were repeated for the PA cephalometric exposures. Since cephalometric landmark identification error was insignificant, the two-dimensional landmark locations obtained from the PA cephalograms could be matched with the three-dimensional data.

Linear regression analyses provided a measure of the relationship between the changes in truth and the cephalometric changes. The results of the regression analyses between the 3-D and the 2-D data showed that all cephalometric landmarks had excellent validity for showing transverse changes since they were able to represent at least 90 % of the actual transverse positions of the dento-facial structures. However, the findings were different along the vertical axis. Ten peripheral radiographic landmarks represented 90 % or more of the changes of their 3D counterparts. Those landmarks that showed less than 90 % of correlation with the changes in truth may be used for cephalometric analysis. However, the potential for inaccurate measurements would increase if these landmarks are used in a cephalometric analysis. The lower limit for what should be considered adequate validity can only be determined by the individual operator.

The four landmarks including Anterior Nasal Spine, Incisor Superior, Incisor Inferior and Menton appeared to have represented the truth only to a limited degree. The inaccuracy of the midline landmarks was largest for Menton, followed by Incisor Inferior, Incisor Superior, and Anterior Nasal Spine. However, this finding is explained by the actual nature of the created manipulations. The vertical increments of change of these landmarks were smaller than the intra-observer error of measurement. Therefore, the validity of these landmarks for vertical measurements cannot be determined in this experiment.

The findings of this study cannot be directly compared to previously published research. Partial comparison could be made with a study by Pirttiniemi et al.³³ In an experiment designed to calculate the horizontal geometric error due to head rotations around the vertical axis it was found that the smallest geometric “error” i.e. the lowest deviation from the midline was recorded for landmarks near the midsagittal plane (InS, InI, Me) and the largest “error” was recorded for the most lateral points (Condylar points, Antegonion). By extrapolation it could be expected to find that those landmarks located in the midline would show the least association with rotational asymmetries, while those on the periphery would be most capable of showing displacements. However, the findings in the present study showed that all landmarks, midline and peripheral included, represented the changes in the horizontal direction with almost equal precision. The lowest association was found for Menton. It should be remembered that the displacement asymmetries created in this study included not only rotations around the vertical axis but also translations and horizontal rotations.

The fact that the changes in the third dimension were significantly related with the ability of only one landmark to show transverse changes pointed out that most peripheral landmarks can show transverse changes regardless of the fact that the changes in the anterior-posterior direction can not be measured on PA films. This finding applies to the vertical manipulations created in this experiment.

In the second part of this study it was found that all horizontal reference lines provided valid measurements of vertical asymmetry. Measurements relative to Orbita Inferior

horizontal reference line were most accurate. However, this finding has to be interpreted within the context of previous research in landmark identification and reproducibility. The vertical identification error of Orbita Inferior is reportedly large²⁰. Therefore, although this line is a valid reference line the landmarks' location error makes it inadequate for measuring true vertical asymmetry in clinical practice. Other points with large identification error along the vertical axis are Orbita Medial, Zygomatico Frontal and Foramen Rotundum.²⁰ The choice of horizontal reference lines is thus smaller than what the present study would suggest.

The most valid vertical reference lines in this study were the perpendiculars to horizontal lines between bilateral cranial landmarks. The results showed that vertical lines connecting two midpoints are not reliable for transverse measurements. In particular, the use of a vertical line drawn between Crista Galli and Anterior Nasal Spine, or Nasion and Anterior Nasal Spine is not justified. One reason for the inability of these lines to adequately represent asymmetric changes could be that one of the two points (ANS or Me) was located on structures that were involved in the asymmetric manipulations. However, Crista Galli-Nasion line was also inaccurate, although both points were stable reference points. The proximity of CG and Na could have been a factor in the poor outcome for this line. Vertical separation between two midpoints that will be used to draw a vertical line has been recommended.³⁴

The four vertical lines that were most reliable, ZF Perp, OI Perp, OL Perp and OM Perp, might provide the most accurate measurements of true transverse asymmetric changes. Once again, landmark identification error needs to be considered. The horizontal envelope

of error of Zygomatico Frontal points, Orbitale Inferior, and Orbitale Medial could be large ²⁰ and these vertical reference lines may not be the best lines to use. The choice of vertical reference line should include the perpendicular lines with high validity, and also the ones constructed relative to landmarks with small envelope of identification error.

It has been suggested that a Best Fit line may be more accurate than other reference lines because of the self-correcting feature incorporated in the method. Namely, when multiple landmarks are located, the point(s) that are obviously off in relation to the other points of the cranium and face can be excluded when drawing the axis. This study confirmed the validity of the Best Fit Line as mid-sagittal reference line. The accuracy of measurements relative to this line was high but not superior to the other reference lines that showed high validity. Therefore, for practical purposes, since the construction of a Best Fit line is more involved it is suggested that a perpendicular line is used for PA analysis of asymmetry.

4.2 LIMITATIONS OF THE STUDY

This study was conducted using one dry human skull that was chosen to represent an "average" or normal human skull. There were no obvious asymmetries, signs of trauma or unusual findings. Although the skull did not have any obvious asymmetry, it has to be assumed that a certain degree of normal cranio-facial asymmetry did exist, as is the case in the general population.³⁵⁻⁴⁰ An existing asymmetry could not have influenced the results of the first study since all measurements were made relative to the neutral positions for the individual landmarks. However, the second study results could have been affected both by the presence, or the absence of appreciable symmetry. If there was an asymmetry in the upper cranial structures, the outcome for the various horizontal and vertical reference lines would have been influenced by this asymmetry. For instance, if Nasion was asymmetric relative to the lateral structures, any lines involving this landmark would have been invalid. At the beginning of the experiment an effort was made to verify that the position of the midline landmarks was lined up but the asymmetry in position of the lateral landmarks was not evaluated. On the contrary, if the skull that was used had less than normal asymmetry, the conclusions regarding validity of the reference lines would once again be limited. Whether the same reference planes are valid for skulls that are not as symmetric remains unknown. In other words, in a real patient with transverse or vertical asymmetries between bilateral landmarks the reference line drawn between such landmarks will be invalid.

Another problem with using one skull might have occurred if there was an asymmetry in the anterior-posterior or vertical positions of left and right Porion. For the PA exposures

the skull was oriented by way of the earposts of the cephalostat. The earposts in the cephalometer orient the head to the trans-meatal line, which may have not be perpendicular to the midsagittal plane.⁴¹

The experimental model that was used in this study allowed the creation of asymmetries of known type (translation, vertical and horizontal rotation), amount (increments of 1.5 to 7.5 mm or degrees) and direction (right or left). The asymmetric manipulations ranged from mild to severe with the objective to maintain them within a range that could be found both in patients with normal asymmetry and with more obvious cranio-facial deformities. Combinations of translation, vertical rotations and horizontal rotations were not investigated since the possibilities are limitless. The manipulations that were created in this experiment did not produce sufficient vertical changes in the region of the four midline points. Therefore, the validity of these landmarks for representing vertical changes could not be determined in this study. Also, the direction of the manipulations in this experiment relationship did not allow to explore a potential relationship between changes in the anterior-posterior axis and vertical changes.

The selection of PA landmarks and reference lines was based on a comprehensive literature review of different PA analyses. Although the intention was to include as many landmarks and reference lines as possible, some landmarks and reference lines might have been omitted.

As pointed out previously, the results of this study are a measure of validity of points and reference lines under the experimental conditions. In clinical practice the error in point

identification combined with projection error may be too great to make accurate measurements from PA Cephalograms and to properly diagnose facial asymmetry. However, this does not lessen the need for use of frontal cephalograms.³³ It has been suggested that to reduce the effect of geometric error in PA cephalometry a reference line and measurement points should be chosen as close to each other transversely and sagittally as possible, e.g. near the anterior midsagittal plane.³³ Finally, the diagnosis of asymmetry should always be verified by means of clinical examination because of the possibility that cephalometric error may exaggerate the measurements.

4.3 SUGGESTIONS FOR FUTURE STUDIES

This study included one skull that was randomly chosen for the experiment. There was no apparent asymmetry or deformity of the cranial structures, and it was assumed that the skull featured normal anatomic proportions. However, variations in skull morphology could alter the outcome, especially the reference lines validity. A future study should include a selection of skulls with normal asymmetries as a control group and a group of skulls with various degrees of upper cranial asymmetries in order to assess the variability of measurements obtained from reference lines drawn between landmarks in the upper cranium.

A suggested future research should also focus on milder range of asymmetries and smaller increments of asymmetric changes. The same methodology as the one used in this study could be used to establish the validity of landmarks in distinguishing between more discrete asymmetries ranging from mild to moderate.

Greater vertical increments of change in the region of the midline landmarks could also be introduced during the experimental manipulations. The validity of midline landmarks for representing vertical changes could be established in this way. Also, by using combinations of vertical and anterior-posterior changes the relationship between the z-axis changes and the ability of landmarks to show vertical changes can be evaluated.

References

1. McWilliam JS, Welander U. The effect of image quality on the identification of cephalometric landmarks. *Angle Orthod* 1981;48(1):49-56.
2. Stirrups DR. A comparison of the accuracy of cephalometric landmark location between two screen/film combinations. *Angle Orthod* 1988;59(3):211-6.
3. Bergersen EO. Enlargement and distortion in cephalometric radiography: compensation tables for linear measurements. *Angle Orthod* 1980;50(3):230-44.
4. Andrew FDA, Warren SL. A study of the distortion in roentgenograms taken at various target-film distances. *Am J Roentg* 1929;22:332-8.
5. Wylie WL, Elasser WA. Undistorted vertical projections of the head from lateral and postero-anterior roentgenograms. *Am J Roentg* 1948;60:414-7.
6. Vogel C. Correction of frontal dimensions from head x-rays. *Angle Orthod* 1967;37(1):1-8.
7. Franklin JB. Certain factors of aberration to be considered in clinical roentgenographic cephalometry. *Am J Orthod* 1952;38:351-68.
8. Hsiao Tin-Hsin, Chang Hong-Po, Liu Keh-Min. A method of magnification correction for posterior-anterior radiographic cephalometry. *Angle Orthod* 1997;67(2):137-42.
9. Ahlqvist J, Eliason S, Wellander U. The cephalographic projection Part II: Principles of image distortion in cephalometry. General considerations. *Dentomaxillofac Radiol* 1983;12:101-108.
10. Houston WJB. The analysis of errors in orthodontic measurements. *Am J Orthod* 1983;83:382-9.

11. Major PW, Johnson DE, Hesse KL, Glover KE. Effect of head rotation on posterior-anterior cephalometric landmark identification. *Angle Orthod* 1996;66:51-60.
12. Van Aken J. Geometric errors in lateral skull x-ray projections. *Neder T Tand* 1963;70:18-30.
13. Ishiguro K, Krogman W, Mazaheri M, Harding R. A longitudinal study of morphological craniofacial patterns via PA x-ray headfilm in cleft palate patients from birth to six years of age. *Cleft Palate* 1974;13:104-126.
14. Solow B. The pattern of craniofacial associations, a morphological and methodological correlation and factor analysis study on young adult males. *Acta Odontol Scandinavica* 1966.
15. Mitgard J, Bjork G, Linder-Aronsons S. Reproducibility of cephalometric landmarks and error of measurement of cephalometric cranial distances. *Angle Orthod* 1974;44:56-61.
16. Houston WJB., Maher RE, McElroy D, Sheriff M. Sources of error in measurements from cephalometric radiographs. *Eur J Orthod* 1986;8:149-51.
17. Baumrind S, Frantz R C. The reliability of head film measurements 1. Landmark identification. *Am J Orthod* 1971;60:111-27.
18. Trpkova B, Major PW, Prasad NGN, Nebbe B. Cephalometric landmarks identification and reproducibility: A Meta analysis. *Am J Orthod Dentofac Orthop* 1997;112(2):165-70.
19. El Mangoury NH, Shaheen SI, Mostafa YA. Landmark identification in computerized posteroanterior cephalometrics. *Am J Ortho Dentofac Orthop* 1987;91:57-61.

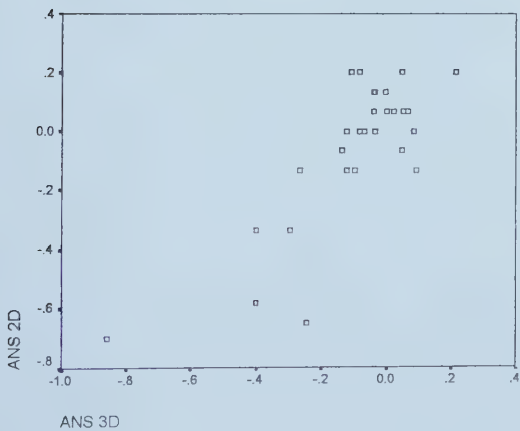
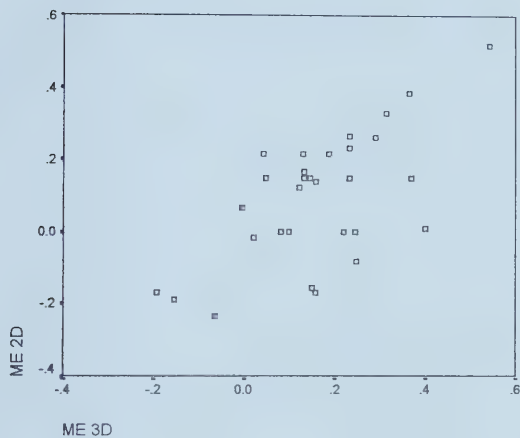
20. Major PW, Johnson DE, Hesse KL, Glover KE. Landmark identification error in posterior- anterior cephalometrics. *Angle Orthod* 1994;64:447-54.
21. Vig PS, Hewitt AB. Asymmetry of the human skeleton. *Angle Orthod* 1978;48:141
22. Hewitt AB. A radiographic study of facial asymmetry. *Brit J Orthod* 1974;2:37-40.
23. Letzer GM, Kronman JH. A posteroanterior cephalometric evaluation of craniofacial asymmetry. *Angle Orthod* 1967;37:205-11.
24. Chebib FS, Chamma AM. Indices of craniofacial asymmetry. *Angle Orthod* 1981;51:214-26.
25. Lund K. Mandibular growth and remodelling processes after condylar fracture. A longitudinal roentgencephalometric study. Academic dissertation. *Acta Odontol Scand* 1974;32:suppl. 64.
26. Stabrun AE. Mandibular morphology and position in juvenile rheumatoid arthritis. A study on posterior-anterior radiographs. *Europ J Orthod* 1985;7:288-98.
27. Alavi D, BeGole E, Schneider BJ. Facial and dental arch asymmetries in CI II subdivision malocclusion. *Am J Orthod Dentofac Orthop* 1988;93:38-46.
28. Grummons DC, Kappeyne van de Coppelo MA. A Frontal Asymmetry Analysis. *JCO* 1987;21:448-65.
29. Harvold EP, Trugue M, Vilorio JO. Establishing the median plane in posteroanterior cephalograms.
30. Cheney EA. Dentofacial asymmetries and their clinical significance. *Am J Orthod* 1961;47:814-29.

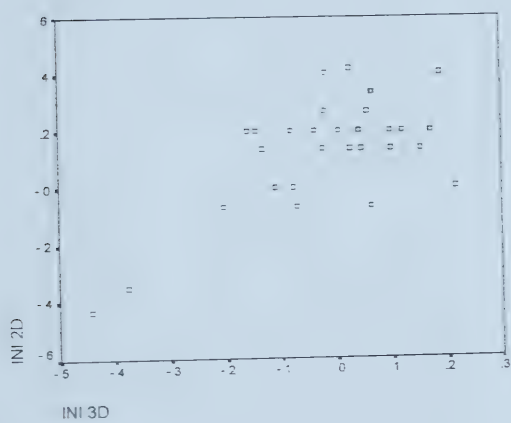
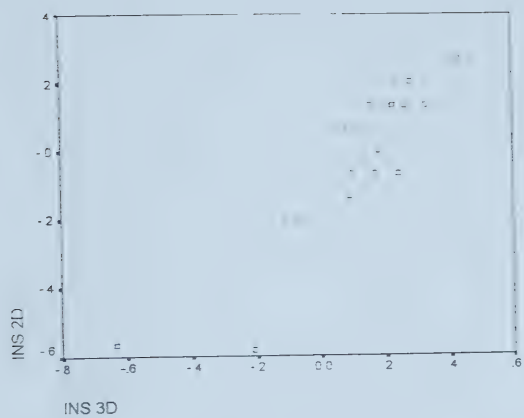
31. Sassouni V. The face in five dimensions. West Virginia University, Morgantown, 1960.
32. Sassouni V, Forrest EJ. Orthodontics in Dental Practice. Saint Louis, C.V. Mosby Company, 1971
33. Pirttiniemi P, Miettinen J, Kantomaa T. Combined effects of error in frontal-view asymmetry diagnosis. *Europ J Orthod* 1996;18:629-36.
34. Johnston DE. The posteroanterior cephalometric radiograph. Masters Thesis 1991;pp46.
35. Lundstrom A. Some asymmetries of the dental arches, jaws and skull, and their etiological significance. *Am J Orthod* 1961;47:81-106.
36. Farkas LG, Cheung G. Facial asymmetry in healthy North American Caucasians: An anthropometrical study. *Angle Orthod* 1981;51:70-7.
37. Vig PS, Hewitt AB. Asymmetry of the human skeleton. *Angle Orthod* 1978;48:141
38. Shah SM, Joshi MR. An assessment of asymmetry in the normal craniofacial complex. *Angle Orthod* 1978;48:141-8.
39. Melnik AK. A cephalometric study of mandibular asymmetry in a longitudinally followed sample of growing children. *Am J Orthod Dentofac Orthop* 1992;101:355-66.
40. Mulick JF. An investigation of craniofacial asymmetry using the serial twin-study method. *Am J Orthod* 1965;51:112-29.
41. Cook JT. Asymmetry of the craniofacial skeleton. *Brit J Orthod* 1980;7:33-8.

Appendix 1

Plots of vertical changes (Δ y- axis) in the 3D vs. 2D data for the four midline landmarks, Menton, Anterior Nasal Spine, Incisor Superior and Incisor Inferior, expressed in millimeters.

The plotted data show that the actual vertical increments of changes of the four landmarks in 3D and 2D measurements are in effect smaller than the error of measurement in the experiment.





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